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Frontispiece

Geotextile bag cut away showing early root restriction of *Dodonaea viscosa* 'Purpurea'.



THE EFFECT OF GEOTEXTILE FABRIC BAG VOLUME AND MEDIA ON THE GROWTH
OF TWO TREE SPECIES

(*Dodonaea viscosa* 'Purpurea' and *Populus x canadensis* 'Tasman').

A thesis
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of the requirements for the degree
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by
R.A. EDWARDS

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Abstract of thesis submitted in partial fulfilment of the requirements
for the degree of Master of Applied Science

THE EFFECT OF GEOTEXTILE FABRIC BAG VOLUME AND MEDIA ON THE GROWTH OF TWO TREE SPECIES

(*Dodonaea viscosa* 'Purpurea' and *Populus x canadensis* 'Tasman')

by

R.A. EDWARDS

Two species of trees grown in geotextile fabric bags indicate that bags may not be a suitable method for long term restriction of growth. This study shows how root restriction occurs in bags and rejects the comparison that bags act in a manner similar to the process of bonsai. Media in bags had a significant effect on trunk diameter, height, total growth, changes in bulk density and the number of root escapes.

Four experiments were carried out to determine the long term effect of geotextile bags, (in ground fabric containers), on restriction of tree growth. The main experiment was a randomised complete block design of five blocks each with two tree species, two media and four bag volumes plus control (no bag treatment equal to the largest bag volume). Trees were planted 3 metres apart in ten rows (2 rows per block), in the field in September 1993. *Dodonaea viscosa* 'Purpurea' was harvested after two years and *Populus x canadensis* 'Tasman' after three years growth. Measurements of height and trunk diameter were made during, and at the end of each growing season. Fresh and dry weights of above and below ground parts were also determined after the trees were harvested.

Results showed media had an effect mainly in the first season, but this effect carried over for the life of the experiment with trees in potting mix larger than trees in field soil for most measurements. Bag volume was generally not significant until the end of the second season's growth. As trees became progressively more restricted within bags, the root : shoot ratio in g/g dry weight reduced. Increased root volume within bags increased media bulk density, indicating extreme levels of compaction especially in the smallest bag sizes.

A second experiment measured the force required to topple trees in bags compared with trees not in bags. *Dodonaea viscosa* 'Purpurea' trees planted for experiment one were wrenched from the vertical axis after two seasons growth, just before the final harvest. Results showed trees in potting mix were more difficult to topple than trees in field soil. There was no difference in force required for trees in 139 l bags or control.

The third experiment assessed the potential for water loss through the wicking effect of the 50 mm of fabric that sits above ground level after planting. The purpose was to determine if the potential drying out of the fabric around the roots affected the process of restriction. Subsequent analysis showed no difference between fabric containers with 50 mm of bag above the surface, at surface level, or if there was no bag. The conclusion was that bag fabric does not dry the area around the roots.

The fourth study considered the response of the geotextile fabric bag when placed under lateral tension. Observations showed fabric samples with an average of 48 needle punched holes per cm² with hole diameters between 200 and 500 µm. Tests showed that when lateral tension was applied to the fabric the number of holes and the diameter of these holes reduced. This suggested roots may have increasing difficulty penetrating the fabric wall as internal tension within the bag increased due to root growth.

Excavations made, where surface cracking was observed, at the base of trees at the end of the third season showed large roots (root escapes), had occurred in *Populus x canadensis* 'Tasman'. Root escapes occurred by exploiting the 3rd dimension of the bag fabric. The restricted root inside the bag produced secondary roots able to enter the wall of the fabric at an oblique angle and grow sufficient length, to exploit the fabric at its weakest point, and finally break out of the bag through 2° thickening. Root escapes were confirmed and numbers recorded after three seasons growth when they were harvested.

KEYWORDS: *Dodonaea viscosa* 'Purpurea', *Populus x canadensis* 'Tasman' bag volume, bulk density, geotextile fabric bags, media, root escape, root restriction.

CERTIFICATE

I hereby certify that the experimental work contained in this thesis was planned, executed and described by the candidate, under the direct supervision of Professor R.N. Rowe and Dr. M.C.T. Trought.

A handwritten signature in cursive script, reading "Richard N. Rowe", positioned above a horizontal line.

R.N. Rowe
(Supervisor)

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CHAPTER 1

INTRODUCTION

People have always endeavoured to control the growth of plants to meet their own needs. These needs have included not only food plants, but as societies became more sophisticated, the desire to improve the 'pleasantness of place', or highlight social status occurred, in part, through the appropriate use of amenity plants. Changes in fortunes and costs associated with planting and maintenance issues have forced the exploration of new ways of doing things. The developments that have occurred over time through science, global transportation systems and technology have all contributed to these changes.

The earliest attempts at pruning to control growth and improve yield are documented as being those of the Egyptians around 3500 BC (Janick, 1972). Other cultures such as those of South America Indians in the Andes, where archaeological evidence suggests they were cultivating potatoes and beans as long ago as 8000 BC (Leach, 1984), are likely also to have attempted pruning. Ancient practices such as topiary (cutting or trimming of plants into weird, fantastic or geometrical forms) has been part of the culture of South American Indians as well as that of ancient Rome, cultures widely separated geographically. Archaeological work at Pompeii uncovered pots and planting soil along garden walls with casts of what was thought to be lemon tree roots. The pots almost always had a hole in the bottom and on three sides (Jashemski, 1992). In the east, cultures such as those of Japan and China respectively have practised the art of 'bonsai' (a plant in a pot), and 'penjing' (miniaturised plants in containers and tray landscapes). According to Huxley et al. (1992), penjing has been practised in China for over two thousand years, at least 800 years before the idea was passed on to Japan and was developed into bonsai. In the seventeenth century Walter Raleigh introduced oranges into England from the New World. His uncle by marriage, Sir Francis Carew, an accomplished horticulturist, grew the oranges in pots and transported these under shelter during the winter months (Black, 1983).

In the large estate gardens that developed in Europe after the Renaissance, garden labour was relatively cheap and controlling the size of trees and shrubs by regularly pruning either the top

or by pruning the roots was common practise. It was not until the end of the first world war that this changed significantly in Europe as a response to changes to social class and wage structures.

More recently with greater urbanisation and the development of cities, urban trees, while highly valued by many, are also major competitors for space, both above and below ground level. This pressure for space continues to increase as the populations of towns and cities develop along with increasingly complex transport and communication systems.

1.1 Street trees

Urban streets are primarily designed for the ease of travel, in today's world usually by the motor car, but also by any other form of wheeled transport available. Footpaths in urban areas are usually provided adjacent to roads predominantly for pedestrian traffic. As well as access for people to travel from one place to another the urban street is a thoroughfare for a vast array of services, both above and below ground level. Typical examples of services in any particular street might include bus shelters, power or telephone lines above ground or below ground; power, telephone, water mains, sewers, storm water drains, gas pipes, or fibre optic cable for future pay TV. In any street the engineers have a major say in the allocation of space for these services, as well as that the road, footpath, property access ways and gutters have first priority in the allocation of surface space at ground level. All of these engineered requirements have had priority over any other kinds of embellishments such as trees and grass berms. Generally services above and below ground are installed to specific offsets from the adjacent property line and it is the positioning of these services that become the limiting factor in whether or not planting may proceed (Mace, 1976).

Trees in existing streets throughout New Zealand have generally been planted after the street and all of its requisite features were in place. Through trial and error horticulturists have established which were the best species to plant with the best results. Taylor (1976) discusses trees suitable for street tree planting in New Zealand and describes the attributes of a number of tree species. Guidelines for producing a tree suitable for planting in a street situation are stated by Henderson, (1976). These suggest a minimum tree height of two metres at planting, a clean trunk of at least one and a half metres and a well - formed top. The tree should be moved a number of times over its life in the nursery so a well-formed fibrous root ball develops. The development of

this root ball would aid in successfully transplanting the tree into the street environment. Day and Bassuk (1994) note that while well-grown landscape trees are recognised as one of a city's greatest assets, growing trees successfully in the modern urban environment is extremely problematic, many trees not surviving the first two years. Reasons given for this include the adverse planting site and the often compacted soils around new building developments.

1.2. Recent measures to control tree growth

While the well-grown street tree is obviously an asset in a city, this view is not necessarily shared by all people and for various reasons. Trees frequently require pruning back to prevent them from using more space than they are initially allocated. In USA it is estimated that between 40 to 50 million trees are annually pruned, producing 50,000 ton of biomass per day to dispose of (Redding et al. 1994). Major changes to the ways in which tree size could be controlled occurred with the development of chemical growth regulators. Harris (1992a) notes that in California in the early 1970's considerable effort were made to control landscape trees with general inhibitors such as maleic hydrazide. The most recent group of chemicals used and being developed are anti-gibberellins, commonly called sub-apical inhibitors because of the way in which they prevent extension growth without killing the terminal meristem of the shoots, as was the case with the general inhibitors. Promising results have been shown with the most recent anti-gibberellins such as Flurprimidol®, Paclobutrazol® and Uniconazole® (Harris, 1992a). Public perceptions of chemical use in the environment along with problems of application create some degree of uncertainty as to the future for these chemicals.

More traditional methods such as selecting suitable clones or genetic selection of dwarfing rootstocks for budding and grafting trees can be options utilised in controlling tree growth. Similarly, landscape architects with a good knowledge of plant selection appropriate to a particular site can be important in minimising maintenance costs associated with tree growth control. All too frequently, these options are unavailable or overlooked.

Recently geotextile fabric bags, (in ground fabric containers), have been promoted as a way of restricting the size of trees and increasing fruit yields for a number of commercial crops Rowe pers comm. (1993), White, (1995). Geotextile fabric was developed initially as a surface material

for use by engineers in building roads. "In 1980 growers at 'Tree Farm' in Guthrie, Oklahoma developed bags of geotextile fabric with plastic bases to reduce costs of harvesting trees for transplanting from the field grown situation" (Sallee, 1987). The bags have also been described as a means of producing semi mature landscape trees which can be extracted from the nursery field grown sites while within the bag and then transplanted into a new environment with minimum growth check. The reasons for the apparent success of the bag system in transplanting trees have been considered in relation to the ability to conserve the greater part of the root system compared with conventional methods which involve wrenching. Sallee (1987) states that "the bags prune continuously, resulting in a root ball packed with feeder roots, 80 percent of which are intact after harvesting". Ingram et al. (1988) found after growing holly in fabric bags and comparing trees without bags' 91% of the total root after one year was contained within the bag, compared with 81% in the same size root zone for no bag trees. The reasons why fruit trees and vines, planted permanently in geotextile fabric bags, appear to produce higher yields relative to smaller tree size is still being investigated (White, 1995).

1.3. **Purpose of this study**

The purpose of this study was to evaluate how landscape trees would respond to long term growth in geotextile fabric bags, planted in the field situation, and whether this system could be used as another practical means of restricting tree size in the landscape. Because experiments at Lincoln University have been growing apple trees, kiwifruit and grape vines in bags for a number of years looking at yield and size control, the possibility of long term control for landscape trees seemed a feasible option. Ideas on how the restriction process may work include the possibility put forward by Rowe (1993), that the turnover of restricted roots in and through the bag wall may cause the plant to respond in a manner similar to that of plants grown in the bonsai system. Roots restricted by the bag fabric develop finer lateral roots and the restricted root portion may break down to allow space for newer and finer roots in some sort of continuum. Reid et al. (1993), using a rhizotron to study the turnover of kiwifruit (*Actinidia deliciosa*) roots, showed only 8% of all roots produced survived more than 252 days, while the cumulative length of roots grown per year was equivalent to about 2.75 times the maximum net length of roots visible. Reiger (1988a) suggests harvest delays of bagged trees will, in fact, curtail top growth and the tree will start to bonsai. The main focus of this study is to evaluate how two vastly different types of tree would respond to

growing in geotextile fabric bags in a medium time frame. Two to three years was the expected growth period needed before useful recommendations could be made. The key questions were will different species of tree act differently in the bagged situation ? Would the bags be suitable for long term growth as in the street tree situation ? Would different media within the bags have any impact? Lastly, if the bag does successfully control growth over the longer term, how does this happen ?

In discussions with Mr Fielding - Cotterell (1993), Senior Arboriculturist of the Christchurch City Council, new ways of controlling the size of trees by non chemical methods would be helpful in maintaining street trees in the City. Tree planting is a major focus of the Arboriculture unit in Christchurch with an estimated 42,000 trees planted in Christchurch streets and an average of a further 30 streets planted each year Watson (1996). The future for trees that need to fit into such a highly regimented artificial environment will need to be considered with the same attention to detail as for other engineered solutions. In part, this exercise is given over to the possibility that the future street tree may be highly specified and its maintenance may be radically different from the situation today where the major effort goes into reducing the crown of the tree in some way. The future may become one where a tree has a higher level of root system management rather than the high levels of maintenance work on trees above ground that exists today. In this way both space above ground and below ground for any particular species of tree might be better managed.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1. Description of species involved in this study

2.1.1. *Dodonaea viscosa* 'Purpurea'

Sydney Parkinson, an artist employed by Sir Joseph Banks on Cook's first voyage of discovery to New Zealand, anchored in Tolaga Bay on the 23rd of October 1769, where he illustrated the akeake (*Dodonaea viscosa*) along with various other New Zealand native plants (Sampson 1985). *Dodonaea* was named after Dodoens a Belgian botanist (Poole and Adams 1986).

Dodonaea L. is a genus of some 50 species belonging to the Sapindaceae, mainly Australian, with scattered members in the tropics and subtropics (Allan 1961). *Dodonaea* Mill. in Huxley et al. (1992). *Dodonaea viscosa* (L.) Jacquin is described as a dioecious, glabrous shrub or tree up to 6m tall or occasionally much more. The bark is reddish brown and falls in flakes, the young branchlets compressed to triangular and are viscid. Leaves are alternate to sub opposite, occasionally three close set, on petioles up to 10mm long. The lamina is thinly coriaceous approximately 4-10cm x 1-3cm, pale green, entire, narrow -obovate to narrow-elliptic, obtuse (rarely subacute, sometimes minutely retuse) gradually narrowed to base. The inflorescence is a terminal, densely flowered panicle approximately 4 mm long. The male flowers have 4 oblong sepals and 8-10 stamens with very short filaments. Female flowers have 4 narrower sepals and an exserted style divided in two parts. The botanical fruit is a compressed capsule which is approximately 15mm x 15mm including broad wings. Sometimes three wings are present (Allan 1961). Thomas Kirk cited in Sampson (1985), describes the heartwood of *Dodonaea viscosa* being so tough that it was used, with good results, as a substitute for brass in machine bearings. Metcalf (1991) comments on the hardness of the heartwood and its use by the Maori as a club and for other weapons.

The distribution of *Dodonaea* is in the North, South and Chatham Islands in coastal and lowland regions from North Cape to Banks Peninsula on the east and a little south of Greymouth on the west. In a footnote Allan (1961) states "As understood at present *D. viscosa* is widespread in tropical and subtropical regions and has many forms. Radlkofer (*Planzenr.* 98g, 1933, 1369) places a Berggren specimen from the Bay of Islands and a Cockayne specimen from Chatham Is. under his var. *vulgaris* (leaves obovate to oblong order), and a specimen collected by H. H. Travers near Wellington under his var. *angustifolia* (leaves of a linear-lanceolate order - both varieties attributed to Bentham in the *Flora of Australia*, 1, 1863.)".

Dodonaea viscosa is a widely cultivated plant (Poole and Adams, 1986). Metcalf (1991) suggests of the fifty or so species of *Dodonaea* about forty are native to Australia, whilst the New Zealand species being described here is also widespread throughout most warm countries in both hemispheres. In cultivation this plant grows between 2.4 and 6m in height (Metcalf, 1991). The species is commonly known as akeake - its Maori name or as hopbush because of the similarity of the fruiting capsules to the hop plant. Huxley et al. (1992), lists the distribution of *Dodonaea viscosa* as South Africa, Australia and Mexico, but curiously does not include New Zealand?

Dodonaea viscosa 'Purpurea' is one of just two cultivars that have been selected from this species. *Dodonaea viscosa* 'Purpurea' was reported by Metcalf (1991), to have been discovered by a Mrs Wilkins on the banks of the Wairau river in the early 1890's. Seeds from this plant, which is apparently self fertile, were grown in her garden and came to the notice later of a Christchurch nurseryman from where the plants were propagated and became widespread in gardens. This plant will produce a range of colours in shades of purple through to green if it crosses with the green leafed species. Where trees of one leaf colour are grown in isolation from others they produce offspring with the same leaf colour. The only other cultivar is one called 'Moonbeam' which is not widely known yet in gardens. This cultivar is described by Metcalf (1991) as having green and grey-green leaves with an irregular creamy-white margin.

2.1.2. *Populus x canadensis* 'Tasman'

Populus x canadensis Moench. (syn. *P. x euroamericana*)

Populus L. belongs to the family Salicaceae and consists of approximately 35 species of deciduous, dioecious trees to about 40m. Huxley et al. (1992), describes the genus as having buds with several unequal scales, often resinous. Twigs are angular to cylindrical in section. The leaves are alternate and usually ovate to lanceolate or triangular, entire, toothed or lobed, on a long, terete, cylindrical or flattened petiole, often with glands at the junction with the lamina. The inflorescences are pendulous catkins which are borne before the leaves. The male catkins are denser than female and arise from the axil of a fimbriate or toothed scale. Each male flower has a toothed or lacinate bract and a stalked, cupulate disc with many stamens with red or purple anthers. The female catkins are longer, the flowers in the inflorescence have an ovoid or rounded ovary in a cupulate disc. The stigmas are 2-4 in number with short or absent styles. The botanical fruit is a 2-4-valved capsule containing minute seeds each with an apical tuft of white hairs. Seeds are released in late spring or early summer. The genus *Populus* is native to Europe, Asia, N. Africa and N. America.

Populus x canadensis was introduced to New Zealand and assessed as a replacement tree for fast growing orchard shelter after the introduction to New Zealand of poplar rust which badly affected the Lombardy poplar (*Populus nigra* 'Italica'). Both 'Tasman' and 'Eridano' were released for soil conservation. During the period 1980 to 1983 45,000 'Tasman' cuttings and wands were distributed by the National Plants Materials Centre, Aokautere. van Kraayenoord (1984) indicated that 'Tasman' and 'Eridano' proved to be the most disease resistant and adaptable of all of the black and balsam poplar clones introduced into New Zealand since 1973.

Populus x canadensis (Canadian poplar) is a tall fast growing tree to 30m with a broad crown. Anon (1984) notes that *Populus x canadensis* 'Tasman' will need regular mechanical trimming as it does not have the narrow growth habit of *Populus nigra* 'Italica' which has been the mainstay of orchard shelter in New Zealand prior to the arrival of poplar rust.

Poplars come from a variety of habitats and require careful selection and siting. Most species according to Huxley et al. et al. (1992), produce debris in the form of seed 'cotton', twigs and leaves, and most have greedy and extensive root systems. Huxley et al. (1992), suggests that

while selected cultivars may be suitable for large gardens, they should be sited at least 40 m from buildings, drains, walls and roads, especially on clay soils where they are known to cause extensive damage to foundations and drainage systems. All poplars are intolerant of root and branch competition and some poplars - *Populus x canescens*, *P. grandidentata*, *P. tremula* and *P. tremuloides* can be propagated by root cuttings or suckers. There appears to be no written documentation that suggests however that *Populus x canadensis* 'Tasman' which is a clonal selection from the two parents *Populus deltoides* x *Populus nigra* can be propagated by root cuttings. *Populus x canadensis* was quite often implicated with damage to buildings usually when growing on shrinkable clay (Cutler and Richardson, 1989).

2.2. Geotextile fabric bags

Geotextile bags have been used since 1980 and commercially available since 1984 from 'Root Control Inc.', Portland, Oklahoma, USA (Reiger, 1988b). Geotextile fabric bags are made of non biodegradable, non woven polypropylene fibres. The bags are cylindrical in shape, open at the top and are planted into a preformed hole in the ground. Trees are then planted into soil or other media within the bag itself. The purpose of the bag is to allow roots of the plant within the bag to exit through the porous fabric of the bag into the surrounding soil. At a stage in the roots development the fabric constricts root growth and new finer roots of a second order develop and can then again grow through the fabric walls, thus the growth is restricted by the bag. The bags produced in the USA. had a polythene glued base and fabric walls, Ingram et al. (1987) observed 50% of all sweet gum (*Liquidambar styraciflua*) in an experiment produced one to four roots that penetrated the polythene bottom of the fabric containers. Bags sourced for this study from Roneby Tree Farm in Melbourne, Australia have fabric walls and bases, with seams stitched on the inside of the bag wall.

The use of geotextile fabric bags in the horticultural industry has largely been confined to nurseries growing trees that retain a higher proportion of the total root system when transplanted than conventionally wrenched trees. Sallee (1987) states "that in more than four years, there is no evidence of root girdling, and that the soft bags prune continuously, resulting in a root ball packed with feeder roots, 80 percent of which are intact after harvest". The major users of geotextile fabric however has been by engineers in roading and erosion control. Fox Waterway Agency (WWW

1997) is designing a way of reclaiming wetland islands inside a large donut of geotextile fabric bag containing dredge material. They state that US Army Corp. Engineers tests indicated plant roots will easily grow through the bag material. Other recent studies have used geotextile fabric to physically constrict root growth in conjunction with chemicals to inhibit root growth. Biobarrier® is a form of geotextile fabric containing polyethylene pellets, at 1.5" spacings, impregnated with Trifluralin® (a slow release herbicide) and has been used with mixed results as a below ground barrier against root invasion by poplar and birch Wagar & Barker (1993). Gilman (1996) worked with live oak (*Quercus virginiana*) and sycamore (*Platanus occidentalis*) using Biobarrier®. He found during a three year period that no roots went through the fabric. Instead, roots went deeper in the soil than control treatments growing below the Biobarrier and regrew into shallower soils 1.2m beyond the barrier.

2.3. Compaction and bulk density

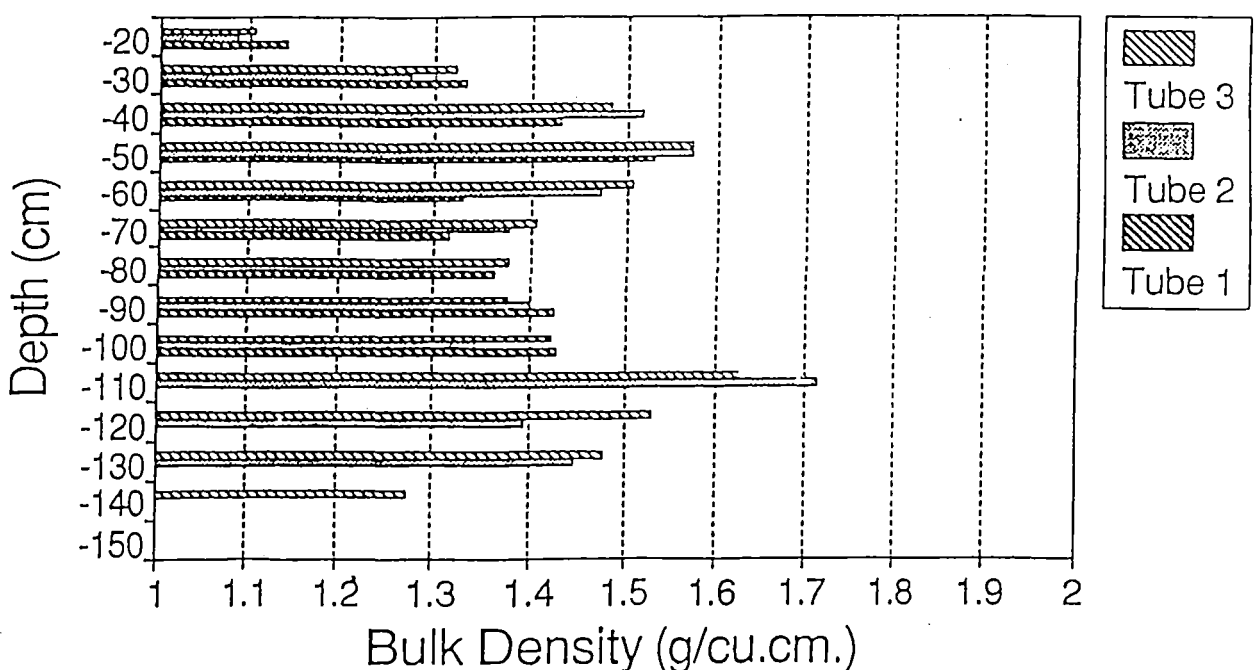
Maximum bulk density and critical moisture content characterise the compactibility of a soil. Water and air supplies to the root system are essential factors for all plant growth. Adequate supplies of these in the soil depend on soil structure. Fertilization should only be considered after adequate supplies of water and air are guaranteed (Zhang & Hartge, 1995).

2.3.1. Bulk density

Bulk density is the density or weight of a given bulk (unit volume) of a soil. The grams per cubic centimetre of soil, including the pores is the bulk density (Donahue et al., 1971). Bowen (1981) describes soil volume as the volume of pores between and among solid materials. The ratio of the volume of voids (pores) to volume of solids is the void (pore) ratio, while the ratio of volume to voids (pores) to total volume of soil is the porosity. The mass of oven dry solids contained in a unit volume of soil is the bulk density. These three parameters are measures of soil compactness. Bulk densities according to Zhang & Hartge (1995) have varying space between solid particles, called porosity or pore space, and in this pore space, varying concentrations of water and air. These are more or less easily movable, depending on gradients within them and flow resistance offered by the matrix of solid particles. This matrix in most cases is considered rigid and pore space therefore a constant.

If the soil structure per unit volume becomes subject to environmental stress it may become compacted. All movements then within the pore system depend on the altered pressure situation within the solid matrix. A change in bulk density is accompanied by a change in porosity. Hartge (1995) found that the compressibility of soils increased with increasing organic content. They also showed that with silt loam and clay soils irrespective of soil texture, as the organic content increased, maximum bulk density decreases and critical moisture content increases. Maximum bulk densities shown for silt loam was 1.76 g/cm^3 and for clay soil 1.57 g/cm^3 . Bowen (1981) suggests as a general rule of thumb (with many exceptions), bulk densities of 1.55, 1.65, 1.8 and 1.85 will severely impede root growth and thus reduce crop yields on clay loams, silt loams, fine sandy loams and fine sands respectively. Pollock (1996) showed a series of bulk density measurements (Table 2.1.) carried out for the Agroforestry experiment at Lincoln University changed markedly at different depths indicating different layers within a soil profile may also affect the rooting pattern of a tree. Patterson (1977) found clayey soil in a mall in Washington DC to be extremely compacted with bulk densities of 1.7 to 2.2 g/cm^3 . In surveys by Day and Bassuk (1994) areas to be landscaped near new residential and commercial buildings were found to have a mean soil bulk density of 1.56 g/cm^3 a 0.5 g/cm^3 increase over adjacent undisturbed areas. These levels of compaction restricted growth for many woody species. (Pan and Bassuk, 1985) and (Chiapperini and Donnelly, 1978).

Table 2.1. Bulk densities measured at different depths in Templeton silt loam (Pollock 1996) (Troxler 4300 Calibration Dry tubes no.s 1,2,3.)



2.3.2. Compaction

Bowen (1981) lists five causes of soil compaction as:

- a) Natural consolidation during soil forming processes
- b) Trampling by animals including humans
- c) Natural shrinkage of soils upon drying
- d) Soil response to pressures and deformations imposed by wheels, tracks and soil engaging tools.
- e) Actions of overburden and of water droplets on water weakened aggregates during rainfall, sprinkler irrigation or flood irrigation.

2.3.3. Consequences of soil compaction

When force is applied to a soil, the major actions within the soil are a rearrangement of particles and a reduction of pore space, especially of large pores. The particle rearrangement and pore space reduction increases both soil compaction and soil coherence. The four factors that change when a soil is subject to an applied load that is sufficient to cause compaction are cited by Bowen (1981) as:

- a) A reduction in the liquid and gas content in the pores
- b) A rearrangement of the soil particles
- c) A change in pressure in the liquid and gases in the pore space
- d) A reduction in the volume of the solid particles.

2.3.4. Mechanical impedance to root growth

Bowen (1981) showed that increases in bulk density reduced root growth, even in soils where aeration should not have been a problem. Gill and Bolt (1955) reviewed studies carried out by Pfeffer (1893) which showed that plants can exert axial (longitudinal) root growth pressures of up to 2500 kPa. during growth. Kibreab and Danielson (1977) showed radish (*Raphanus sativus*) roots ceased enlarging their diameter when subject to radial constraints of about 850 kPa. Taylor and Gardener (1960) showed if a medium is easily deformable, roots enter and grow until some factor other than mechanical impedance controls elongation rate. In most situations, roots grow partly through existing pore spaces and partly by moving aside particles. Barley (1976) suggested the radial expansion of roots would reduce soil resistance immediately in front of the root tip. Harris (1992a) indicates the oldest cells of the root cap slough off and lubricate the movement through the soil. He also notes that roots compared to shoots have no regular branching pattern and follow the path of least resistance. Russell and Goss (1974) showed that a 20 kPa. pressure applied to a glass bead system reduced the elongation rate of barley (*Hordeum vulgare*) roots by 50 percent and a 50 kPa. pressure reduced the rate by 80 percent. As the pressure increased, the roots became shorter and larger in diameter. Henry (1993) showed that decreasing media pore diameter in a rigidly contained system reduced volume, length and dry weight of the roots of grape plants. He also found root growth to be completely halted by pore diameters of less than 200µm mean equivalent pore neck diameter (MEPND), with the percentage of total pore volume that needed to be occupied for root growth to be significantly reduced estimated to be between 25% and 45% at 365µm MEPND and between 50% and 65% at 1885µm MEPND. Taylor and Ratcliff (1969) showed the roots of cotton plants decreased in number over a range of soil types as soil resistance increased. They also demonstrated a reduction in the number of roots produced in cotton as soil mechanical resistance increased, however even though penetrometer resistance of 700 kPa. reduced cotton root elongation 50%, 2000 kPa. penetrometer resistance was required to reduce peanut root elongation by 50%. Materechera et al.(1991), showed compacted soil restricts rooting area, slows or halts root penetration and results in increased branching and radial thickening of the roots.

2.3.5. Water

Penetrometers show an increase in bulk density as soil water content decreases, although the exact change depends on soil type (Bowen, 1981). Water in soil therefore affects mechanical impedance. The water volume in a soil is never static and is continually changing as soil volumes lose water through surface evaporation, drainage and through root extraction. Water is also gained from flows from zones of low potential to zones of high potential. Irrigation also affects water availability and reduces mechanical impedance. Day and Bassuk (1994) found resistance to penetration in a clay loam soil decreased from 3.5 mPa. to 2.1 mPa. when volumetric soil moisture increased from 27% to 40%. Water breaks the cohesive bonds between soil particles and causes the average size of the structural unit in the surface layer to be reduced (Bowen, 1981). In compacted soils water moves more slowly due to insufficient macropores. Pores may, however, remain water filled for longer than in a well aggregated soil. When plants are restricted by compacted soils, the smaller volume of soil available for exploitation by the roots results in a smaller water reservoir available to the plant. (Experiments carried out by Krizek et al.(1985) with soybeans in small pots, even though watered several times per day, showed restricted shoot growth. Restricted rooting volume led to a reduction in total root surface area, which in turn affected the amount of water the root could take up, even though water was freely available (Krizek et al., 1985). Klepper (1991) suggests in drier years root : shoot ratios for a given plant increase with deeper rooting. New roots proliferate in soil only where there is adequate soil water and the ratio decreases when soil moisture levels increase. Krizek et al. (1985) working with soybeans, showed soil moisture stress decreased nitrogen and phosphorus concentrations in both roots and leaves, leaf water potentials, stomatal conductances, the initiation rates of new leaves and photosynthetic rates per unit leaf area and increased dry matter allocation to the roots at the expense of the shoots. Root restriction on the other hand showed little effect on any of these parameters.

2.3.6. Oxygen

Oxygen diffuses approximately 10,000 times more slowly through water than air. (Nobel, 1991). In compacted soils oxygen is likely to be more limiting when soil pores are filled with water and potentially a major problem, where drainage is also poor. These limitations to aeration may be exacerbated by increased oxygen consumption by roots and microbes during the growing season

(Yelenosky, 1964). Brouwer (1963) showed large differences in the growth between aerated and non aerated bean plants in water culture. Valoras et al.(1964) working with avocado trees, found root growth stopped when oxygen diffusion rates dropped below $0.20\mu\text{m}/\text{cm}^2/\text{min}$. Plant responses to oxygen levels have been shown to interact with mechanical impedance (Day & Bassuk, 1994). Tackett & Pearson (1964) working with cotton, showed at varying soil bulk densities growth stopped at different oxygen levels. Cotton roots at a bulk density of $1.3\text{ g}/\text{cm}^3$ stopped growing at 5% oxygen levels whilst at a bulk density of $1.5\text{ g}/\text{cm}^3$ stopped growing at 10% oxygen levels. No root growth occurred for any oxygen level at a bulk density of $1.9\text{ g}/\text{cm}^3$. Currie (1984) in a laboratory study showed that soil compacted to a bulk density of $1.54\text{ g}/\text{cm}^3$ from an original bulk density of $1.04\text{ g}/\text{cm}^3$ reduced gas diffusion by 38% when dry, but this went up to 82% when the soil was wet. The effect of compaction is clearly intensified while soils are wet. In soils where drainage is adequate compaction may not necessarily limit oxygen levels, or plant growth. Taylor & Burnett (1964) found that poor aeration was not a factor in soils with bulk densities of 1.75 to $1.88\text{ g}/\text{cm}^3$. Oxygen levels alter throughout the year in subsoil as the water tables rise and fall, Yelenosky (1964) measured oxygen levels below a road at a depth of 30 cm and in an adjacent uncompacted site. Beneath the road oxygen levels were 4% and adjacent to it 20%. During the dormant season oxygen levels beneath the road were found to have returned to 20%.

Certain species such as *Taxodium distichum* (swamp cypress) have adaptive strategies in pneumatophores, (a form of aerial root) which sits above the water and is able to absorb oxygen (Huxley et al. 1992).

2.3.7. Nutrients

Harris (1992a) states nitrogen is the nutrient that is universally deficient. Nitrogen is the nutrient to which trees commonly respond, with the most visible response being in increased shoot growth. Potassium is rarely deficient except on fairly specific soils, although Phosphorus is often deficient in New Zealand soils. Brouwer et al (1961) working with barley, maize and ryegrass showed nitrogen applications reduced the root : shoot ratios. If nitrogen was withheld from solutions the root : shoot ratio increased and then stabilised. Where nitrogen levels were low, additional nitrogen favoured total plant growth, but with a much larger proportion favouring shoot growth over root growth. Gilbertson et al. (1987) observed that applications of nitrogen to birch

seedlings in the first year of growth added 50% more root than shoot growth, and that the greater the application the greater the root : shoot ratio. Syvertsen & Smith (1996) working with citrus growing in lysimeters showed increased nitrogen levels increased canopy volume and leaf nitrogen concentrations, but there was no effect on fibrous root dry weight. They also found different rootstock's used had an effect on the efficiency of nitrogen uptake. Ingestad and Lund (1979) found when suboptimal levels of nutrients in birch seedlings were increased 5% over the day before, plant growth increased approximately 5% over the previous day also. Brouwer (1963) showed plants grown with low nitrogen and phosphorus levels had higher root : shoot ratios than in media with ample supplies of nitrogen and phosphorus. When phosphorus is deficient in soils, additions of phosphorus stimulate total tree growth. If nitrogen is limiting, Harris (1992a) suggests roots will grow proportionately more than the top and more nitrogen is shunted to the leaves, which may keep chlorophyll and photosynthesis proportionately higher in relation to the total nitrogen available. Brouwer (1963) observed changes were dependant upon the internal nitrogen status of the plant. The presence of nitrates in the root medium was not the key factor in determining the root : shoot ratio, but the reserve of the nitrate in the plant was. When the nitrate containing solution was changed for a solution without nitrate, the reaction was delayed until the nitrate reserve in the plant was depleted. Ingestad and Lund (1979) found when optimum nitrogen levels misted on tree seedling roots were markedly reduced, shoot growth reduced, leaves yellowed and root growth reduced, although to a lesser degree. Roots also grew longer with less branching. If the lower level of nitrogen was maintained, which was proportional to the trees growth rate, the healthy green leaf colour returned and concentrations of starch were found to be comparable with trees growing at the higher nitrogen levels. Larcher (1995) suggests an excess of nitrogen leads to a decline in mycorrhiza. Mycorrhizal fungi are responsible for the uptake of most phosphorus and nitrogen in forest trees. They also assist in heavy metal uptake such as iron and trace elements as well as toxic elements such as cadmium and lead. Al Sahaf (1984) working with tomatoes found root confinement increased the efficiency of utilisation of K and Ca in two cultivars. He also found confined plants had a lower concentration of Ca and Mg in the leaves, whereas K was the same in all treatments. Root confinement had no effect on the levels of Ca, Mg or K in the fruit. White (1995) working with apples with roots confined in geotextile fabric bags found root restriction increased concentrations of calcium within the fruit. Al Sahaf (1984) found root confinement increased the efficiency of the utilisation of Ca, Mg & K. suggesting that the efficiency of incorporation of minerals into dry matter production can be affected by genetic and external

environmental interactions. Al Sahaf (1984) also suggested that the total mineral content in any plant is approximately proportional to its dry weight.

2.4. Plant growth processes

"The amount and quality of tree growth are determined by heredity and environment, operating through physiological processes" (Kozlowski, 1991).

2.4.1. Role of the root system

Roots have a number of functions - anchorage, absorption of water and nutrients, storage of carbohydrates and production of new roots as well as growth regulators, in particular cytokinins.

2.4.2. Root containment by volume

Henry (1993) found that reducing container volume from 4600 mls to 150 mls decreased the length, volume and dry weight of the roots of grape vines by more than 50%. Al Sahaf (1984) working with tomatoes showed plants with confined roots retarded the growth of vegetative parts in all cultivars. The dry weight of leaves, stems and roots was reduced while that of fruits was not affected. Root confinement in an experiment over a three month period was also associated with a reduction in the root : shoot ratios compared with non confined plants. The root : shoot ratio in confined-released plants remained as low as the continuously confined plants.

Al Sahaf (1984) growing tomatoes observed that during the vegetative stage of growth, root confinement increased the proportion of the dry weight of stems and reduced that of leaves compared with non confined plants. After the transition to the reproductive phase, plants showed a new pattern of dry weight distribution mainly brought about by the growth of fruits. The increase in the proportion of dry weight allocated to the top of confined plants was not equally shared by all top components. The proportion of the stems and fruits increased while that of leaves decreased. Root confinement changed the morphology of the leaves. The total and average leaf surface area of confined plants were smaller than those of non confined plants. White (1995) working with apples in geotextile fabric bags found the trunk cross sectional area of trees decreased linearly as bag

volume was reduced, but that growth differences were not related to canopy volumes. White (1995) also found that smaller trees as a result of root volume restriction had a higher fruit yield per trunk cross sectional area than larger non confined trees, although the total fruit yield was less than the larger non confined trees.

Al Sahaf (1984) found that root morphology also changed in response to physical confinement of the root. Confined root systems were more branched, and when the confined roots were released to larger containers the numbers of lateral roots increased rapidly resulting in a greater ratio of root number : root length compared with those of continuously confined and non confined roots (Al Sahaf, 1984). Results indicated that the roots of confined plants on a dry weight basis can support a greater shoot growth due to an increase in the water and mineral uptake activity of the root per unit root length. Al Sahaf (1984) speculates that this could be a result of root confinement on two factors that affect the uptake of water and minerals. These are a reduction in the diffusive resistance to the influx of water and minerals into the root, and an increase in the cation exchange capacity of the root surface. It is also possible that root confinement leads to a more effective use of assimilates by the root system to enhance the initiation and growth of more lateral roots which may be more efficient relative to their length in taking up water and nutrients. This would imply that the activity of the root system increased as the demand from the plant top increased with a negligible increase in the dry weight of the root. Henry (1993) working with grapes, found that decreasing container volume increased the percent of pore volume occupied by roots and reduced root volume, root length, root number, shoot length and dry weight. By reducing pore diameter he found root density and root specific dry weight increased with shorter roots, visibly contorted and more branched. Henry (1993) also suggested that a major disadvantage with restricting root volume and root growth is that the buffering capacity of the vine to absorb water and nutrients is reduced against events such as drought increasing the risk of yield reduction or of crop loss.

2.4.3. Role of the shoot

In woody dicots the main stem or trunk of the tree supports branches which in turn support leaves. Leaves are essential for photosynthesis and the manufacture of carbohydrate which is utilised or stored by the whole plant. The position of branches in a tree allows for the 'best'

orientation possible for leaves to intercept light. The branches also provide sites for flowers and the subsequent development of fruit. The synthesis of growth regulators determining plant growth and form, primary extension and secondary thickening are also fundamental roles of the shoot.

2.4.4. Root : shoot ratio

The root : shoot ratio is usually given as the weight of the roots to the weight of the top. Homeostasis, or the functional equilibrium that exists between plant parts for most plants as described by Brouwer (1963), is generally accepted Klepper (1991). Brouwer (1963) suggested that the relationships between root and shoot weight are changing continuously, whilst that between evaporation and root weight remains the same. Chung (1983) working with cucumbers found that the specific activities of an organ were more closely related to the physiological conditions of the opposite organ whose function was under stress. Harris (1992b) indicates that the root : shoot ratio is 1:5 or 1:6 for most trees under normal conditions. He also suggests that except for root injury, a reduction in the root : shoot ratio is almost always in response to favourable growth conditions such as favourable weather, increased fertilisation, or irrigation, aeration or pest control. Brouwer and Kleinendorst (1965) working with ryegrass, found that if supplied with an adequate level of nitrogen, the root : shoot ratio is about 1:3 and it remained fairly constant for the life of the experiment. Harris (1992b) suggests that if the trunk of a tree is taken out of the ratio, the ratio of roots : shoots is about 1:1. Klepper (1991) states as a general rule, annual crop plants show high root : shoot ratios during germination and stand establishment. This ratio gradually decreases during the growing season, especially during the reproductive stage. Perennial plants as a general rule show flushes of activity with patterns of assimilate distribution that change depending on the growing season. Klepper (1991) suggests that the diversity of root diameter and tissue composition makes any relationship between the roots dry weight and its functionality quite complex to determine for dicots. McLaughlin et al. (1980), working with white oak (*Quercus alba* L.) found 50-60 year old trees averaging 410 kg dry weight had only 13.5 kg of current leaves and twigs. He suggests that the dry weight of perennials are mixtures of old and new tissues which makes interpretations of root : shoot ratios difficult.

2.4.5. Interrelationship between root & shoot system

Experiments have looked at root pruning with different species (Buttrose & Mullins 1968, Richards & Rowe 1977a,). Root pruning has been shown to reduce shoot growth rates, though not in proportion to the roots removed Harris (1992b) and depending upon the timing of the operation increase flower set (Ferree 1992). Root pruning in younger vigorous plants that flower on one year old wood has been shown to encourage flowering and fruiting at an earlier age (Harris 1992a).

Kays et al. (1974) showed roots of beans encountering mechanical impedance increased ethylene production in the roots. Ethylene was seen to increase the root diameter of beans. Sun and Bassuk (1993) showed high levels of IBA (indolebutyric acid), caused ethylene to build up in rooted rose cuttings preventing bud break. Ethylene is also associated with the process of fruit maturation and the hastening of leaf senescence. Nooden and Leopold (1988) showed applications of ethephon to leaves hastened senescence. Blackman & Davies (1985) working with maize suggest abscisic acid produced by the roots controls stomatal activity in the leaves. Carmi & Heuer (1981) working with beans, found they could overcome much of the stunting of shoots in pots with restricted roots by applying gibberellic acid and, or benzyladenine. Nooden and Leopold (1988) suggest that in leaves, closure of the stomata usually initiates senescence.

Al Sahaf (1984) working with tomatoes showed smaller leaves of confined plants had an improved photosynthetic capacity, with a higher concentration of chlorophyll in the leaves and better light interception - improving the productivity of the leaves. The root : shoot ratio has been shown to decrease in low light conditions, Van Dobben (1962) and in low root temperatures. (Cooper & Thornley, 1976). Richards & Rowe (1977b) working with peach seedlings, found that applications of BAP (6-Benzylaminopurine), increased calcium levels in leaves that had previously been reduced by root confinement. Hartmann and Kester (1975) showed cytokinins promote bud initiation, although applications to pea cuttings showed growth of roots and shoots sensitive to both temperature and application rates. Kramer & Kozlowski (1979) suggest that assimilates are partitioned in a plant on a priority basis; young fruits and seeds > young leaves and stem tips > mature leaves > cambium > roots > reserves. Klepper (1991) showed in an annual carbon budget for *Pinus sylvestris* L. that well over half of the current years photosynthate was utilised in the root

system. Klepper (1991) found both growth and maintenance respiration in the roots of *Pinus sylvestris* L. were greater than in the shoots. Neuman (1993) found working with hybrid poplars that inducing root restriction and root hypoxia (oxygen deficiency around the root zone), resulted in plants with fewer and smaller leaves than control plants. He also found in *in vitro* measurements of leaf discs that restricted roots and root hypoxia treatments led to increased starch levels in leaves, while the concentrations of abscisic acid and zeatin riboside-type cytokinins in xylem sap was reduced in the roots of restricted plants.

Ingram et al. (1987) found total carbohydrate content of primary root samples of live oak (*Quercus virginiana*) and southern magnolia (*Magnolia grandiflora*), was greater for trees that had roots confined in ground fabric containers than for trees with unrestricted root growth. They also found with sweet gum (*Liquidambar styraciflua*), that unrestricted tree roots had the highest starch levels. An increase in carbohydrate levels in root systems produced in geotextile fabric bags for transplanting is believed to be the major reason why rapid root development occurs after transplanting, assuming all other environmental and physiological factors are not limiting. Kramer and Kozlowski (1979) suggest that secondary growth and storage has a lower sink priority than does fruit. Al Sahaf (1984) and Hameed et al. (1987), found with tomatoes that dry matter is partitioned to the fruit rather than the permanent structure and storage - assuming fruit are present

2.4.6. Conclusion

Plants respond in a multitude of ways to changes in the environment both above and below ground level. Many of the responses by plants are not fully understood. Mechanisms have evolved within plants over time that have enabled plants to develop various strategies to survive short term fluctuations in the plants environment. Plants with secondary thickening such as trees are able to store carbohydrate within many parts of the tree for use at a later date. They may not survive indefinitely however if extreme conditions do not improve.

CHAPTER 3

MATERIALS AND METHODS

3.1. Experiment 1

The objective for this experiment was to study the effects of root restriction by using a range of different sized 'Root Control Bags' (geotextile fabric bags) and two different growing medium on the subsequent growth of *Populus* 'Tasman' and *Dodonaea viscosa* 'Purpurea'.

3.1.1. Cutting preparation of *Populus* 'Tasman'

Cuttings of *Populus* 'Tasman' were taken on the 26th of March 1993 from trees growing in a shelter belt in the Horticultural Research Area at Lincoln University. All trees in the shelter belt were from the same clonal material and appeared uniform in every respect. Cutting material was taken from six of the trees in the shelter belt. Cuttings were prepared so each was a similar length and diameter. Slight variation in cutting size occurred because of bud placement. Leaves were stripped and cuttings were prepared approximately 30cm in length, with a base diameter of between 11 and 16 mm. Sufficient cuttings were made to ensure the required number would be available for the trial later. All cuttings were placed in a medium consisting of 50% pumice and 50% washed river sand. No rooting hormone was applied to any of the cuttings. Cuttings were made with a horizontal cut just below the node at the base and a cut angled to run moisture away from the bud, just above the top bud. Twenty five cuttings were inserted in eight 200 mm diameter plastic pots. Four pots of cuttings were placed on a hot bed in full light and warm air temperatures in a durolite house. The other four pots were placed on a hot bed in a low light shed, with considerable ventilation and cooler air temperatures. Cuttings in the durolite house showed roots penetrating from the base of the pots after 20 days. The pots of cuttings were shifted off the hot base on to an adjacent bench on the 26th of April. Cuttings in the low light cool air situation showed root penetration from the base of the pots after 23 days and were shifted to the durolite house with the other cuttings on the 29th April. Because of the obvious leaf growth some cuttings were starting to make in the durolite house, cuttings were moved outside into a shade house to slow growth until

planting could be made in spring. Cuttings, once placed in the cool temperature shade house environment, quickly lost their leaves and moved into a dormant phase.

3.1.2. *Dodonaea viscosa* 'Purpurea'

Plants of *Dodonaea viscosa* 'Purpurea' were obtained from the Department of Horticulture Nursery at Lincoln University. This was a seed - grown line of trees, collected from a single *Dodonaea viscosa* 'Purpurea' seed parent. Trees were grown on in planter bags (P.B.3s) and looked uniform in size, but not colour. Some of the trees were strongly purple coloured, others were a mixture between purple and green and some were green only. As part of the experiment it was thought appropriate to compare a species with obvious colour variation to see whether the other treatment effects imposed would be great enough to over ride any inherent genetic seed variation. This species was also thought to have different root growth characteristics from the cutting grown poplars, being less invasive. Trees grown by City Council nurseries as street or park trees are frequently grown by a variety of means including seed.

3.1.3. Plot Preparation

The trial area was prepared on 26 and 27th of August 1993. A 30 x 30 m land area was required. The grassed area available was mown, measured and marked out, the grass clippings were raked away from the lines and rows sprayed with Preeglone (a dessicant herbicide). On 30th and 31st August lines were again put out from east to west and from north to south at 3m intervals across the plot area in order to mark out where the trees were to be planted. Labels indicating where each treatment was to go were placed in the appropriate areas. Dead grass remains were chipped away and the circumference of each hole required was marked using a device made for the purpose.

3.1.4. Field Soil

The field soil used in bags in this experiment is classified as Templeton silt loam. The area where the trees were planted is Templeton silt loam over sand, the depth of top soil varies only slightly over the trial area and averages between 40-50 cm. The planting site is level, well drained

and sheltered on all sides. The bulk density of the soil at planting was 1.11 (based on an average of two measurements from close to the soil surface). Particle size distribution varies depending on the depth sampled, but based on Watt & Burgham's (1992) work is made up of approximately 15% clay, 65% silt, 15% fine sand and 5% medium sand. All of the soil that was used in the bags was excavated from the holes dug in the field to accommodate the bags. Each of the holes was excavated to the precise bag diameter and depth required. Excavated soil was placed in a trailer and taken back to the nursery where it was shredded in order to both mix the soil and produce a fine tilth that could easily be used in the actual bag filling and the planting of the trees, into the prepared holes. Sub soil from the base of the large holes that was excavated was spread evenly along the surface of the rows between treatments. The pH of the field soil was 5.6. No additional fertiliser was applied to the soil used in bags or in the general trial area.

3.1.5. Potting Mix

Few growers (if any today), grow containerised trees and shrubs in medium containing soil, however field grown trees in fabric bags are grown in field soil. It was considered appropriate to compare trees in experiment one growing in field soil in geotextile bags with others growing in potting mix in geotextile bags in the field situation. Trees grown like this in the commercial nurseries are then likely to be transplanted to new sites where the ground soil would be significantly different to that in the bag.

The potting mix used in the trial was prepared using 80% composted crushed bark and 20% washed crusher dust manufactured sand. A total quantity of 4m³ was made up containing 30 kg of 12 -14 month release Osmocote 15-3.5-9.1 plus 16 kg of Dolomite lime. The bulk density of the potting mix was 0.75 (based on an average of two measurements). Bunt (1976), notes firm potting increases the bulk density of this type of media, so should be interpreted as a guide only. The measured pH was 5.2

The source of the bark used is from Leithfield (Spurway, pers comm. 1996). It is *Pinus radiata* bark that has been stockpiled in a heap for eight months. The bark is then processed through a hammermill and sieved to remove coarse material (material > 10 mm). The finer material remaining has 1.5 kg of calcium ammonium nitrate (80%) plus calcium carbonate (20%) and is then stockpiled in heaps to compost for not less than 6 weeks. The pile is turned 2-3 times per week and

after a minimum of 6 weeks is sold as Composted Horticultural Bark (Collingwood 1994). The pH of the composted horticultural bark at this stage is 4.9. The bark has the following approximate particle size composition:

0-0.6 mm	5%
0.6-1.4 mm	21%
1.4-2 mm	8%
2-5 mm	40%
5-10 mm	26%

Water holding capacity (WHC) of the bark has been measured at 46%, while the Air Filled Porosity (AFP) was measured at 28%. (Note: Using the Australian Standard AS3743-1989 a standard container height of 12 cm is assumed. For containers with a height of >12 cm the AFP increases, whilst containers <12 cm the AFP decreases). (Leithfield bark is currently supplied by Canterbury Landscapes).

The sand used in this experiment is manufactured ('WAP5') washed crusher dust with jagged edges and ranging in size up to 5 mm Spurway pers comm. (1996). Sand has a high volume of solid material (64%) and a very low total pore space TPS (35.5% volume) with 14.8% air space. Cation exchange capacity (CEC) for sand is extremely low (Goh and Haynes 1977).

Analytical Services Laboratory in Hamilton (1996) measured the Air filled porosity of the combined bark/sand potting mix used at 15% with a normal range for this media of between 12% and 25%. Water holding capacity was measured at 42% with a normal range for this type of medium between 35% and 50%.

Table 3.1. A comparison of percentages by particle size for medium used

Diameter range (mm)	Silt loam %	Bark 80% +	Sand 20%
<0.002 (clay)	15		
0.05-0.002 (silt)	65		6% (0.075)
0.25-0.05(very fine & fine sand)	15		10% (0.15)
0.5-0.25 (medium sand)	5	5% (0-0.6)	12% (0.3)
2.0-0.5 (Coarse sand)		21%(0.6-1.4) 8% (1.4-2.0)	14% (0.6) 19% (1.18)
5.0-2.0		40%	25% (2.36) 14% (4.75)
10.0-5.0		26%	

(Note: figures above for sand and bark are separate, but in the Potting mix used were combined in a ratio of 4 bark : 1 sand). Information used to develop the above table is from Donahue et al. (1971), Collingwood (1994), Fulton Hogan pers comm.(1996) and Watt and Burgham (1992).

3.1.6. Planting

Populus 'Tasman' cuttings were planted on 3 September 1993, followed by *Dodonaea viscosa* 'Purpurea' which was planted on 8 September, 1993.

3.1.7. Stakes

Because of the bushy nature of the *Dodonaea viscosa* 'Purpurea' trees it was decided that each should be staked. One metre bamboo canes were placed to the north east of each plant and the tree fixed to the stake in one position by a single tie. A 'Max Tapener' was used to fix the tie. As the trees increased in size the bamboo stakes were replaced with larger stakes one to the north and one to the south of each tree. All trees in the experiment were supported with flexible rubber

inner bicycle tubes at approximately 50 cm from the ground. Both *Populus x canadensis* 'Tasman' and *Dodonaea viscosa* 'Purpurea' were staked, according to guidelines in Harris (1992a), with 2 wooden stakes in July 1994. Stakes were set the same distance from the trunk of each species, the distance being equal to approx 25 cm outside of the largest bag size

3.1.8. Rabbit activity

Rabbit activity in the trial area was a continual threat to the experiment. Initially each plant was coated with 'Thiropel'®, (contains 10% Thiram as a paste), from the base of the trunk to include the lower branches to a height of around 45 cm. An electrified rabbit proof fence, (with approximately 4000 volts passing through it), was also used as a further precaution. In spite of best efforts, maintaining a fully charged battery did not always happen and rabbits did occasionally enter the trial area and dig around the roots of some trees. The effect of this could not be quantified.

3.1.9. Irrigation

An irrigation system was installed with individual drippers to each tree. Water was supplied at 1Lh^{-1} to each tree via a single dripper for the periods in which irrigation was supplied. Water was applied mainly over the summer period for the duration of the experiment. Failures occurred with this system and there were constant problems with drippers clogging up and requiring cleaning. There was also two separate occasions where the system blew apart causing major soil scouring at the north end affecting a few trees in one block. Soil had to be removed from the base of these trees where it had covered the bags. It is unknown if this had any effect on the final results.

3.1.10. Experimental Design

The experiment was designed as a Randomised Complete Block. There were five blocks each block containing one replicate for each of ten treatments times two separate tree species randomly arranged. A total of 50 trees of each species, 100 trees in total.

Treatment factors

Five replicates per treatment. (Every tree in each of 5 blocks was one replicate - See Appendix 1)

- a. **Geotextile fabric bag sizes used.** There were four bag sizes, 4, 24, 65 and 139 litre bags and a control. The control was a hole excavated to the same dimensions as for the 139 litre bag only. It was assumed the preparation of a no bag hole size of one diameter only would provide a suitable control for all of the bagged treatments in assessing if the bags affected growth. In the results only the 139l no bag treatments and 139l bagged treatments were compared directly.
- b. **Types of media used.** Two different types of media with differing physical and nutritional properties were selected for trees to grow in within the bags and the controls. The media employed were Templeton silt loam and a soilless potting mix.
- c. **Species used** Two tree species were chosen for this experiment *Populus x canadensis* 'Tasman' and *Dodonaea viscosa* 'Purpurea'

3.1.11. Layout of trees

All trees were spaced 3m apart in the row and between rows. Treatments were completely randomised within the five blocks. Each block consisted of two rows of ten trees orientated in a north-south direction.

3.1.12. Initial Measurements

Initial measurements of the height and stem diameter of *Dodonaea viscosa* 'Purpurea' were made to see whether there was any significant variability in plant size. The colour of the foliage of *Dodonaea viscosa* 'Purpurea' was ranked and recorded to see if the effect of leaf colour had any significance to the final results. Measurements for each individual plant were taken and recorded (See Appendix 2). The diameter of each of the cuttings of *Populus x canadensis* 'Tasman' were also recorded. The lengths of each cutting were compared during preparation to ensure a consistent size (See Appendix 3).

3.1.13. Subsequent measurements

Measurements of both height and diameter were made over each of the growing seasons and again at the end of each season. A mark was painted on the trunk of each tree with white plastic paint at a standard height of 30cm from the ground, so that the diameter was measured at the same point each time. As the diameter of the trees grew the paint was reapplied at the end of each growing season. Trunk diameter was based on an average of two measurements of the trunk, the second measurement approximately 90° on the trunk at the same height from the first. Measurements of height initially involved using a graduated telescopic pole, as trees grew larger a hypsometer was used. Measurements using the hypsometer were based on the average of two measurements of the tree from a different angle each time. Final height measurements were made after harvesting the tree with a tape measure while the trees were horizontal. Soil cracking at the base of the *Populus* 'Tasman' trees was noticed toward the end of the second growing season. Measurements of the crack length and direction of cracking were made for all replicates of *Populus* 'Tasman' before harvesting in the third year of growth.

3.1.14. Harvesting of trees

A severe frost in the winter of 1995 affected some of the *Dodonaea viscosa* 'Purpurea' trees within two blocks. Because of the deaths of some trees these were harvested at the first available opportunity. Two complete sets of replicates for each treatment were harvested to include all those affected by frost. All of the roots were dug, including those within the bag and those outside of the bag. Digging the roots outside of the bags was extremely time consuming and even with great care not all of the roots may have been harvested. All subsequent harvesting of roots included only roots within bags and as much of the control roots that could be found within a reasonable time period. Because many of the leaves were obviously dead for the *Dodonaea viscosa* 'Purpurea' fresh weights were not measured and for all other harvests of this species only dry weight were used. The three remaining blocks of *Dodonaea viscosa* 'Purpurea' were harvested later in the year and results for dry weights, height and other measurements were aggregated together with the results of the earlier two reps. harvested for the purposes of analysing the results. Where the roots outside the bag were measured for only 2 reps. these results are shown separately. All of this species were harvested within a few months of each other at the end of the second growing season.

Populus x canadensis 'Tasman' were harvested over a three month period in 1996 at the end of the third growing season in the field. The trees were harvested while in a dormant state, without leaves.

By the end of July 1996 all poplar trees were dug from the ground, the outside roots were washed and root escapes were then counted for each replicate in the experiment. Each root escape was also measured (diameter) at the point of exit at the bag wall. A root escape for this experiment is defined as a root that has been able to penetrate the geotextile fabric and continue increasing in diameter in a more or less unrestricted manner and is not able to be easily broken at the bag wall. In contrast restricted roots also penetrate the geotextile fabric, but tend to develop a bulbous area on both sides of the geotextile fabric linked by a small restricted portion of root up to approximately 3 mm in diameter and are easily broken at the point of restriction.

Measurements of both fresh and dry weights were made. Calculations of root weight and volume were made by weighing bags containing media and roots, plus trunk base cut at ground level. Bags were weighed after harvesting using electronic digital scales suspended on a chain between the bucket of the tractor and the bag being weighed. Each bag containing media and roots was then lowered into a water tank to measure weight by volume displaced. This exercise was repeated three times and weights averaged. The fabric bags were then removed and root washing using high pressure hosing was done, taking care to retain as much root as possible by washing through a sieve. Each root mass was then lowered into a tank of water and weighed, the assumption that 1 litre of water displaced was equal to 1 kilogram. Roots were reweighed three times each and averaged by the same process as above. Roots were then cut up and dry weighed. In the process of doing so a considerable amount of media was found to be jammed inside the centre of root matrix and had to be removed with a welders hammer. The compacted media found inside the root matrix plus the fabric bags were weighed and subtracted from the earlier fresh weights to provide a net fresh weight for roots. The tops of the poplar were weighed fresh in the field by using electronic digital scales suspended on an inverted table on sheep scales. Trees were cut up and dry weight was determined. Roots were placed in drying ovens at 70° C for approximately 7 days. After that time samples were weighed and recorded and then reweighed 24 hours later. Providing no weight changes, all samples were then finally weighed and recorded.

3.1.15 . Bulk density and media compaction calculations

Bulk density is a measure of the weight of a given volume of soil and is usually expressed as g/cm³. Harris (1992a) states bulk density is a useful measure of soil compaction and for a given soil, the greater the bulk density, the more that root growth and function will be restricted. Measurements for this experiment were made taking two separate one litre samples from two different sides of the field where the trees were planted. The soil was dried for 24 h⁻¹ at 70°C before weighing, two separate samples of potting mix were also dried for 24 h⁻¹ before weighing. Each sample of potting mix was tapped on the bench five times in its container to simulate the normal potting up situation. Potting mix was added as necessary to make up the volume to exactly for each 1L sample before drying.

Calculations to determine the media compaction and bulk density at harvest for the *Populus x canadensis* ‘Tasman’ used the following formula;

$$\text{Index} = \frac{\text{B.D (c)}}{\text{B.D (o)}} = \frac{\frac{\text{W(o)}}{\text{V(o) - V(r)}}}{\frac{\text{W(o)}}{\text{V(o)}}} = \frac{\text{W(o)}}{\text{V(o) - V(r)}} \times \frac{\text{V(o)}}{\text{W(o)}} = \frac{\text{V(o)}}{\text{V(o) - V(r)}}$$

Key (c) = calculated at harvest, (o) = original, (r) = roots, B.D. = bulk density, V = volume, W = weight

3.1.16. Analysis of results for all experiments

Results for each of the measurements made were analysed on Minitab for Windows Release 9.2 using analysis of variance. Graphs were produced on SigmaPlot Version 2.0. (Jandel Corporation). The effect of bag volume was analysed for each species separately from the controls and the largest bag size 139 litres was analysed with control (139 litre hole no bag). Where the F test was significant at 0.05 or greater, LSD's were calculated to compare the means for both 139 litre bag versus Control (139 litre no bag) and field soil versus potting mix. Regression analysis was at the P ≤ 0.05 level. Regression analysis was not done on any data that included control treatments. Growth on the Y axis of histograms represents each one or more separate seasons growth. Final growth represents the total of all seasons growth.

3.2. Experiment 2

The objective of this experiment was to obtain a comparative assessment of how much force it would take to pull over a tree in each of the different geotextile bag treatments. This could then be equated to the likelihood of trees blowing over. The hypothesis being that a smaller root system largely confined within a geotextile fabric bag would offer little resistance to wind throw, particularly if the bag had little effect on the size of trunk and branches.

3.2.1. Materials and Method

In late 1995, before harvesting the remaining three blocks of trees of *Dodonaea viscosa* 'Purpurea', an assessment was made of how much force was required to pull trees over simulating wind throw for each of the ten treatments. Each treatment involved the three replicates still to be harvested. A 400 lb (182 kg) Salter Spring Balance was placed between a Morris 3/4 ton (763 kg) Lever Pull Hoist and a tractor drawbar. The tractor had the hand brake applied so it would not move. A seat belt was placed around the trunk of the tree 150 mm above ground level. (At the painted mark where trees had previously been measured). The seat belt was attached to a the lever pull hoist which was attached to the spring balance. The spring balance was attached to a chain which was attached to the drawbar of the tractor by a metal ring on the end of the chain. The lever pull hoist was tensioned up until the tree broke at the roots and started moving from the vertical plane. At the point of breaking an audible cracking sound occurred and the pressure on the scales dropped very quickly, so care was needed to keep an eye on the scales as tension was applied. Measurements of force were read from the balance at the critical breaking point. This was the point at which the pressure was no longer sustained when an attempt to apply more force was made. The measurements in pounds below were later converted to newtons. (one pound equalling 4.4482 newtons).

3.3. Experiment 3

The objective for this experiment was to assess if geotextile fabric bags act as wicks facilitating faster evaporation from the media adjacent to the bag when part of the bag is above ground as recommended, compared with bags set with the top buried at the same height as the surface level of the media.

3.3.1. Introduction

Harris (1992a), states that "paper mache or burlap containers must not be exposed above the soil, because either one can act like a wick, drying itself and the soil below". Others have suggested the possibility that geotextile fabric bags may act in a similar manner, hence the effect on subsequent reduction in tree growth may be a result of the drying around the zone of the bag itself. Directions that accompany information about the using geotextile bags suggest the following; "Key points to watch in planting RCB's are:- make the hole or trench 50 mm shallower than the height of the bag; leave the bottom hard so the bags won't sink; the top of the bag should remain 50 mm above ground level" (Root Control Systems Pty Ltd., 1993).

An experiment was set up on the 1 September 1994 to determine if geotextile fabric bags did act as wicks. The experiment consisted of 3 treatments, bags with the top exposed 50mm above the medium, bags planted so the top was level with the medium and a control with no bag. There were 5 replicates for each treatment arranged in a randomised block within a glasshouse.

3.3.2. Materials and method

Root restriction bags of one size (4L) were filled with well mixed crushed bark and planted into larger 10 litre plastic buckets also containing the crushed bark from the same source. In total each bucket was filled with 5kg of bark. All buckets were new, the same make and colour. The bags containing crushed bark were planted at two different levels within each bucket - (top of bag at surface level and top of bag at 50 mm above the surface). A control with no bag was included as the third treatment. Each treatment replicate was labelled individually before adding water and bark, with a label attached to the bucket handle. Four litres of water was check weighed (4000g) and

added carefully to the bark in each bucket completely saturating the bark surface and any bags as the water was applied to each container. Each container, and bag was weighed before the crushed bark and water was added.

3.3.3. Measurements

Every bucket including the crushed bark and bags within were then weighed at 7 day intervals to determine if there was a differing rate of water loss. Each bucket was weighed on electronic scales, weights were recorded and each bucket was replaced one position differently in order back on the bench. This was done to minimise the possibility that one position may have been differently affected to another within the experiment. The weight of bucket and bag was subtracted from the gross weight for each replicate measured. Results are based on weight loss for each period measured. Loss over time was analysed for each treatment. The experiment was started on 1 September 1994. and the last measurement taken on 17 November 1994.

3.3.5. Demonstration of wicking effect

A second and subsequent minor experiment was set up on 14 March 1995 to further consider the hypothesis that geotextile fabric bags may act as a wick drawing water up through the bag away from the roots.

3.3.6. Materials and methods

Two strips were cut out of a geotextile fabric bag. The strips were 105 mm in length by 30 mm wide. A piece of wire was inserted through the fabric at one end and this was attached to a retort stand. This allowed both strips to hang at the same height. One strip was soaked in water for one minute, the other was not. A beaker containing a dilute solution of rhodamine dye was then placed at the base of the strips so that the lower few millimetres was soaking in the solution. Strips were left in with the base in the solution until no further movement of dye in the strips was observed.

3.4. Experiment 4

3.4.1. Introduction

To further evaluate how the process of restriction by geotextile fabric bags affected the root system of the trees being studied the characteristics of the fabric that the bags were made from was investigated.

Initial observations of geotextile fabric under a low powered stereoscopic microscope showed the presence of a number of needle punched holes. A centimetre square was drawn on the same area on both sides of the fabric and an attempt was made to count the number of holes. This proved difficult as the number seemed to vary depending upon which side was being viewed despite the fact that the same square centimetre of fabric was being looked at. The fibres of the fabric on being stretched laterally gave the impression of both altering the hole diameter and the actual number of holes. In order to confirm this samples were reassessed using a projection microscope in the Wool Science at Department at Lincoln University.

3.4.2. Materials and methods

Tests on the geotextile were carried out using a projection microscope. The holes were counted manually from square centimetre sections cut from the fabric. Holes from five samples of fabric were counted. Further fabric samples of 150 x 40 mm were cut. Sample one was cut in the line with the direction of the needle punched holes, sample two at 45° and sample three at 90°. Each sample was extended lengthwise between clamps of an Agritest tensiometer at a force of 20 newtons.

3.4.3. Analysis of results

Observations were made and recorded on the number and size of holes within the geotextile fabric both before applying lateral tension and after. Standard deviations were calculated.

CHAPTER 4

RESULTS

4.1. Experiment one: The effect of geotextile bags and media on the growth of two tree species.

The results for this experiment for each of the growth parameters measured for both *Dodonaea viscosa* 'Purpurea' and *Populus x canadensis* 'Tasman' are presented in the following order;

- Section 4.1. the effect of media on growth in bags (four bag sizes - 4, 24, 65 and 139 l),
- Section 4.2. the effect of media on growth (control 139 l no bag and 139 l. bag),
- Section 4.3. the effect of bag volume on growth (four bag sizes - 4, 24, 65 and 139 l),
- Section 4.4. the effect of bag or no bag on growth (control 139 l no bag and 139 l. bag).

The way in which the control was set up for this experiment largely determined the presentation of results. The control was a hole size equal to the largest bag diameter, which enabled comparisons to be made between the growth of trees in the bag or no bag situation. It also allowed a comparison between media in bags or no bag treatments. (There were no similar controls for the other bag sizes). The other main effects compare the effect of media on tree growth over all bag sizes and of bag volume on tree growth. Where significant interactions occurred these are dealt with in the appropriate section

4.1.1. Effect of media on trees grown in bags (excludes controls)

4.1.2. Height

Dodonaea trees (Figure 4.1.1.), grown in bags filled with potting mix were taller than those in field soil by the end of the first growing season. There was no difference in the height growth rate of trees in soil or potting mix for the second season. The cumulative effect of the first and second seasons growth produced *Dodonaea* trees that were taller when grown in potting mix than trees in soil. *Populus* trees showed a trend ($P=0.102$), in the first seasons growth, growing taller in potting mix. There was no effect of media on the height of *Populus* measured separately for both the second and third season of growth. There was no cumulative effect of media on the height of *Populus* measured at the end of two seasons, or at the end of three seasons growth.

There was a significant interaction between media and bag volume at the end of the second seasons growth for *Dodonaea*. The cumulative effect of two seasons approached significance (Table 4.1.). However, the results for the interaction showed the greatest growth is in both 24 l and 4 l bags with tree growth reducing as bag volume increased. This result is not easily explained, but suggests that the trees simply had not been in the bags for sufficient time before harvesting. There were no similar interactions for *Populus*.

Table 4.1. Interaction between media and bag volume for *Dodonaea* height
(mm) after two seasons growth

Bag volume (l)	Soil	Potting mix
4	60.2 bc	36.2 a
24	46.6 ab	74.15 d
65	42.2 a	37 a
139	53 bc	40.6 a
P = 0.026		
LSD = 8.078 (level of significance .05)		

4.1.3. Trunk diameter

Both species produced larger trunk diameters in year one as a result of being grown in geotextile bags containing potting mix, rather than field soil. *Dodonaea* trees continued this effect for the second season (Figure 4.1.2.), but *Populus* trees did not produce trunk diameters that differed significantly. The cumulative effect of two seasons growth produced trees with larger trunk diameters in potting mix. *Populus* trees in the third seasons growth were larger in bags with potting mix than in bags with field soil. The cumulative effect of three seasons growth for *Populus* approached significance, with trunk diameters being largest in trees grown in potting mix (Figure 4.1.3.).

The only significant interaction between bag volume and media on trunk diameter was for *Dodonaea* for the first seasons growth (Table 4.2.). The interaction again showed trees in the 24 l bag with the largest diameter with progressively smaller diameters shown for trees in larger bag sizes. This interaction also indicates the root system of *Dodonaea* may not have had sufficient growing time to be influenced by the bag volume and little notice should be made of this result, even though the figures suggest significance.

Table 4.2. Interaction between media and bag volume for *Dodonaea* trunk diameter (mm) after one seasons growth

Bag volume (l)	Soil	Potting mix
4	13.76 b	16.48 c
24	13.65 b	22.17 e
65	12.38 a	22.18 e
139	13.32 ab	20.86 d

P = 0.047

LSD = 1.14 (level of significance .05)

4.1.4. Populus fresh weight

The above ground portions of *Populus* -trunk and branches (Figure 4.1.4.), and the below ground portions - mainly roots and some trunk were weighed separately. Note roots outside of the bag were not harvested. Both portions of the trees were heavier when they had been growing in potting mix in bags as opposed to field soil in bags.

4.1.5. Dry weight

Dodonaea harvested after two years growth (Figure 4.1.5.), and *Populus* trees harvested after three years (Figure 4.1.6.), showed all measurements for both above ground and below ground level parts of the tree were heavier when grown in potting mix than when grown in soil. Note roots outside of the bag are not included. The roots of *Populus* trees were sorted while fresh into roots with a diameter greater than 5 mm and roots less than 5 mm fresh. The dry weights of roots in both categories were heavier from trees grown in potting mix (Figure 4.1.7.).

Interactions between bag volume and media for root dry weight for roots both <5mm and >5 mm diameter when sorted fresh were significant for *Populus* (Tables 4.3. and 4.4.).

Table 4.3. Interaction between media and bag volume for *Populus* roots <5mm
(separated fresh before dry weighing) after 3 seasons growth (dry weight g).

Bag volume (l)	Soil	Potting mix
4	38.04 a	41.34 a
24	164.26 b	122.76 b
65	185.66 bc	410.6 e
139	344.88 d	633.06 f

P = 0.001

LSD = 43.92 (level of significance .05)

Table 4.4. **Interaction between media and bag volume for *Populus* roots >5 mm**
(separated fresh before dry weighing) after 3 seasons growth (dry weight g).

Bag volume (l)	Soil	Potting mix
4	456.5 a	796.6 a
24	1625.2 b	1618.2 b
65	1931.3 b	4140.3 d
139	2396.9 bc	6711.1 e

P = 0.001

LSD = 553.24 (level of significance .05)

Two replicates for each treatment of *Dodonaea* harvested included both roots inside the bag and outside of the bag. (These trees were harvested at the end of two growing seasons because they were affected by a heavy frost. The remaining trees were harvested later in the year), (Figure 4.1.8.). Trees grown in potting mix in bags compared with trees in soil in bags produced a greater root dry weight for roots both inside and roots outside of the bags. The above ground level tree dry weight was also heavier for trees grown in potting mix.

4.1.6. Surface root crack length of *Populus* ‘Tasman’ after three seasons growth

There was a trend (P=0.166), indicating greater cracking length for trees grown in potting mix compared with trees grown in field soil in bags on the measured length of surface root cracks.

4.1.7. Root escapes in *Populus* ‘Tasman’ after three seasons growth

There were a greater number of root escapes from trees grown in potting mix in bags than from trees grown in field soil in bags (Figure 4.1.9.).

4.1.8. Relative root and shoot production

After two seasons growth, a higher proportion of the total dry matter occurred in the trunk and branches of trees grown in field soil when compared with trees grown in potting mix in bags. *Populus* trees at the end of three growing seasons produced similar results (Figure 4.1.10.).

4.1.9. *Dodonaea viscosa* ‘Purpurea’ Leaf colour

There were no effects based on leaf colour of *Dodonaea* and media.

4.1.10. Effect of root growth and geotextile bags on media compaction

To determine how changes in the media developed over the three seasons growth for *Populus*, comparisons between dry weight of roots and root volume were made. A media compaction ratio was calculated by dividing the original root volume by the original bag volume less the root volume. The calculated bulk density for both soil and potting mix were then multiplied by the above ratio to provide a measure of the bulk density at the time of harvesting (Table 4.5). An analysis of morphological root density based on the results, (root volume cm³ divided by root dry weight in grams), was also carried out. Neither bag volume or media showed any effect on morphological root density.

Table 4.5.Media compaction index calculated for *Populus* ‘Tasman’ after 3 seasons growth

Bag volume (litres)	Bulk density at harvest g/cm ³
4	1.803 a
24	1.148 b
65	1.065 b
139	1.026 b

P = 0.018

LSD = 0.53 (Level of significance 0.05)

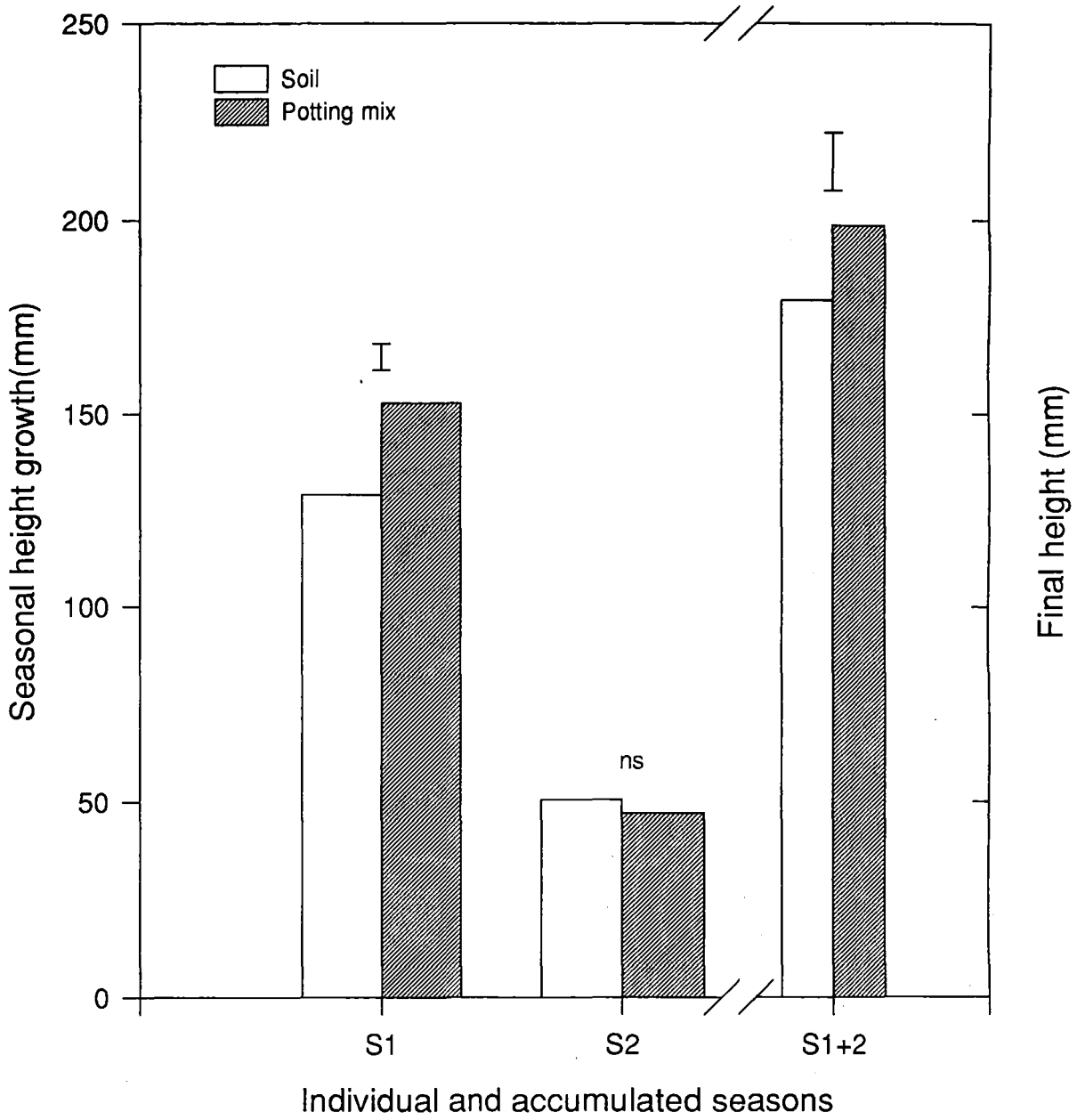


Figure 4.1.1. The effect of media on *Dodonaea* increase in height for individual and accumulated seasons growth for all bag sizes.

First season (S1) Tr Anova P = 0.000

Second season (S2) Tr Anova P = 0.110

Total of all seasons (S1 + 2) Tr Anova P = 0.013

LSD at 0.05 are represented by a capped vertical bar.

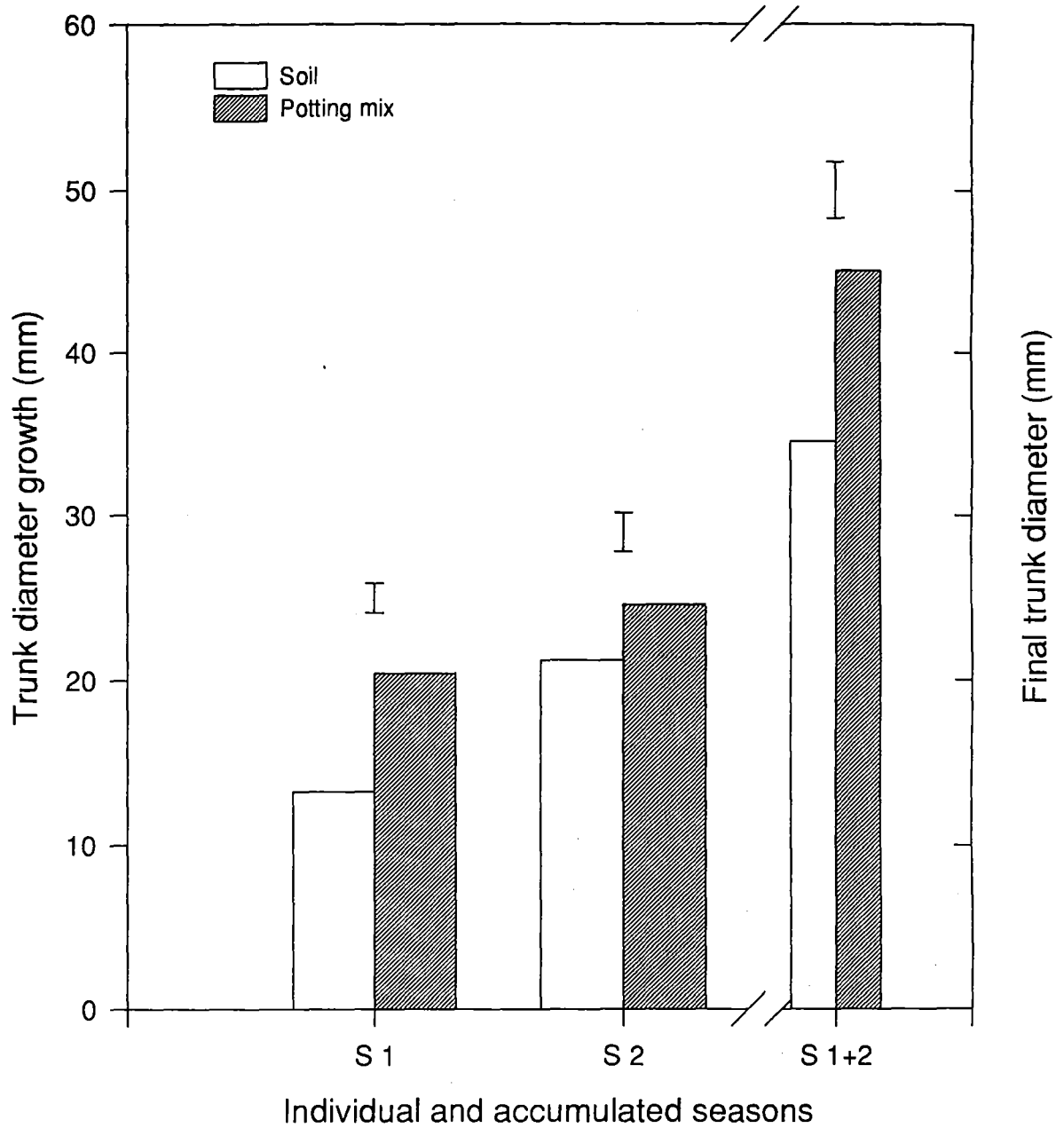


Figure 4.1.2. The effect of media on the increase of trunk diameter for seasonal and accumulated seasons growth of *Dodonaea* for all bag sizes.

First season (S 1) Tr Anova P = 0.000

Second season (S 2) Tr Anova P = 0.007

Total of all seasons (S1 + 2) Tr Anova P = 0.001

LSD at 0.05 are represented by a capped vertical bar.

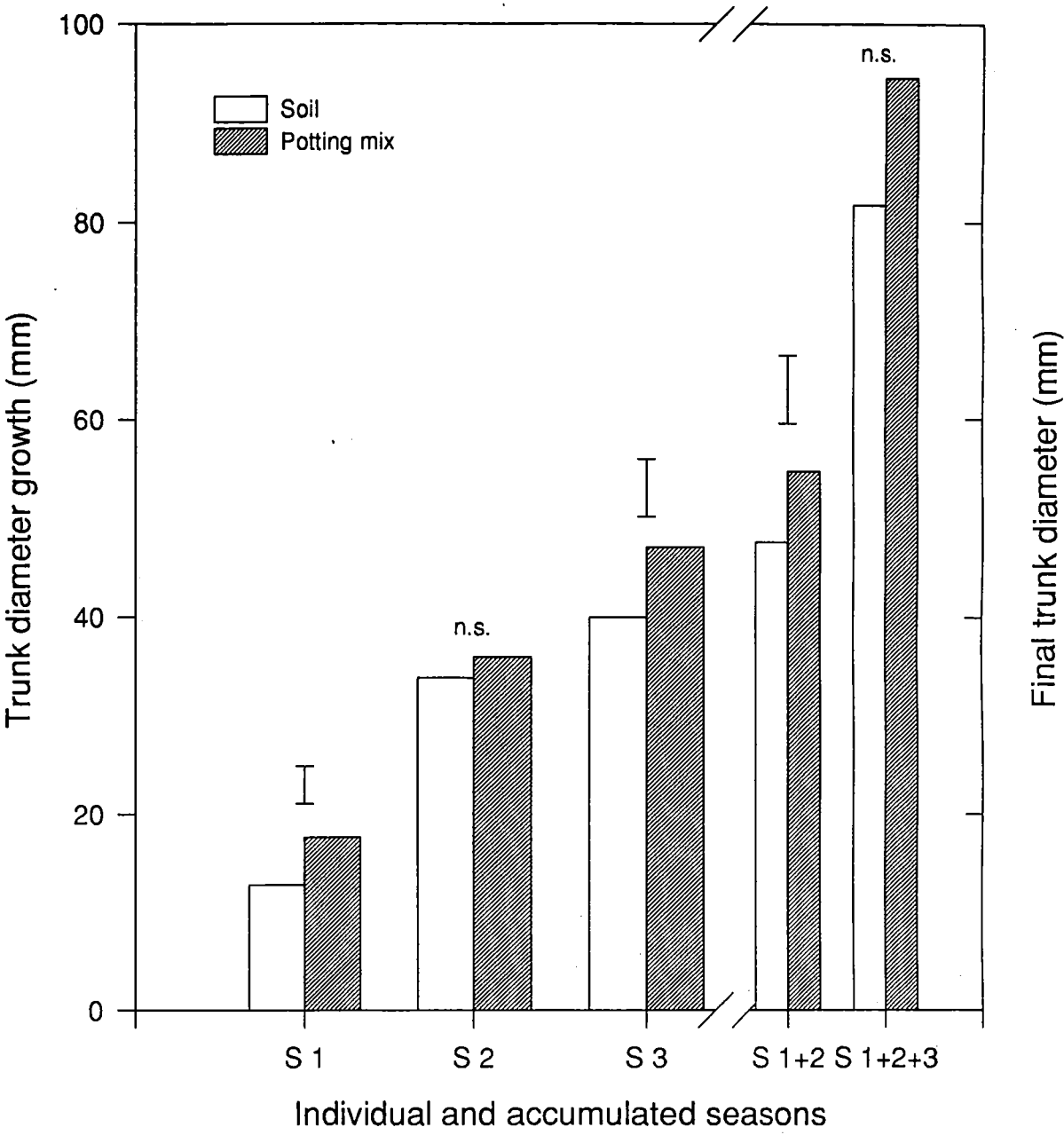


Figure 4.1.3. The effect of media on *Populus* trunk diameter for all bag sizes for individual and accumulated seasons growth.

First season	(S 1)	Tr Anova	P = 0.014
Second season	(S 2)	Tr Anova	P = 0.343
Third season	(S 3)	Tr Anova	P = 0.027
First & second season	(S 1+2)	Tr Anova	P = 0.052
Total of all seasons	(S 1+2+3)	Tr Anova	P = 0.097

LSD at 0.05 are represented by a capped vertical bar.

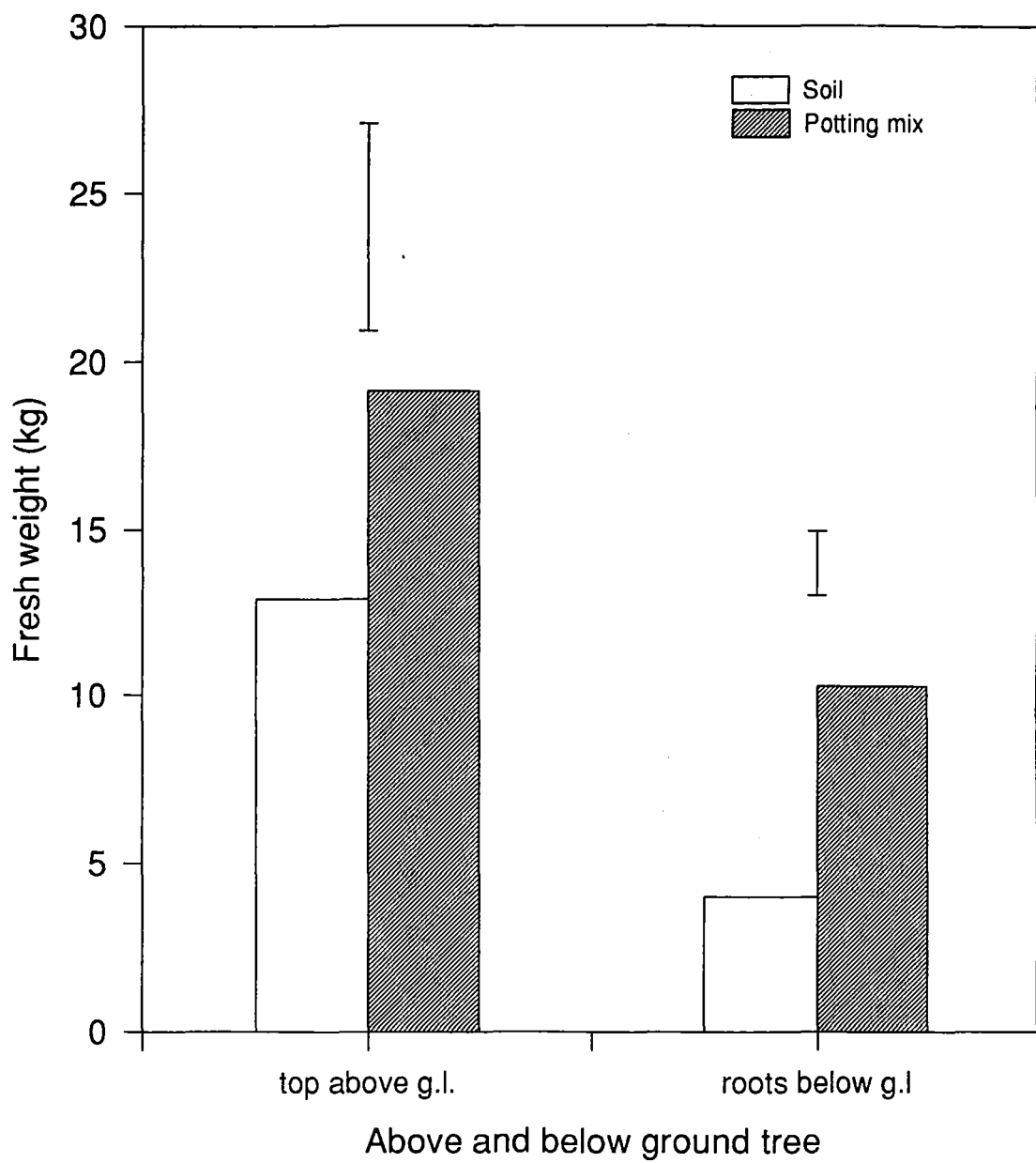


Figure 4.1.4. Effect of media on *Populus* fresh weight after three years growth

Top Tr Anova P = 0.046

Roots Tr Anova P = 0.000

LSD at 0.05 are represented by a capped vertical bar.

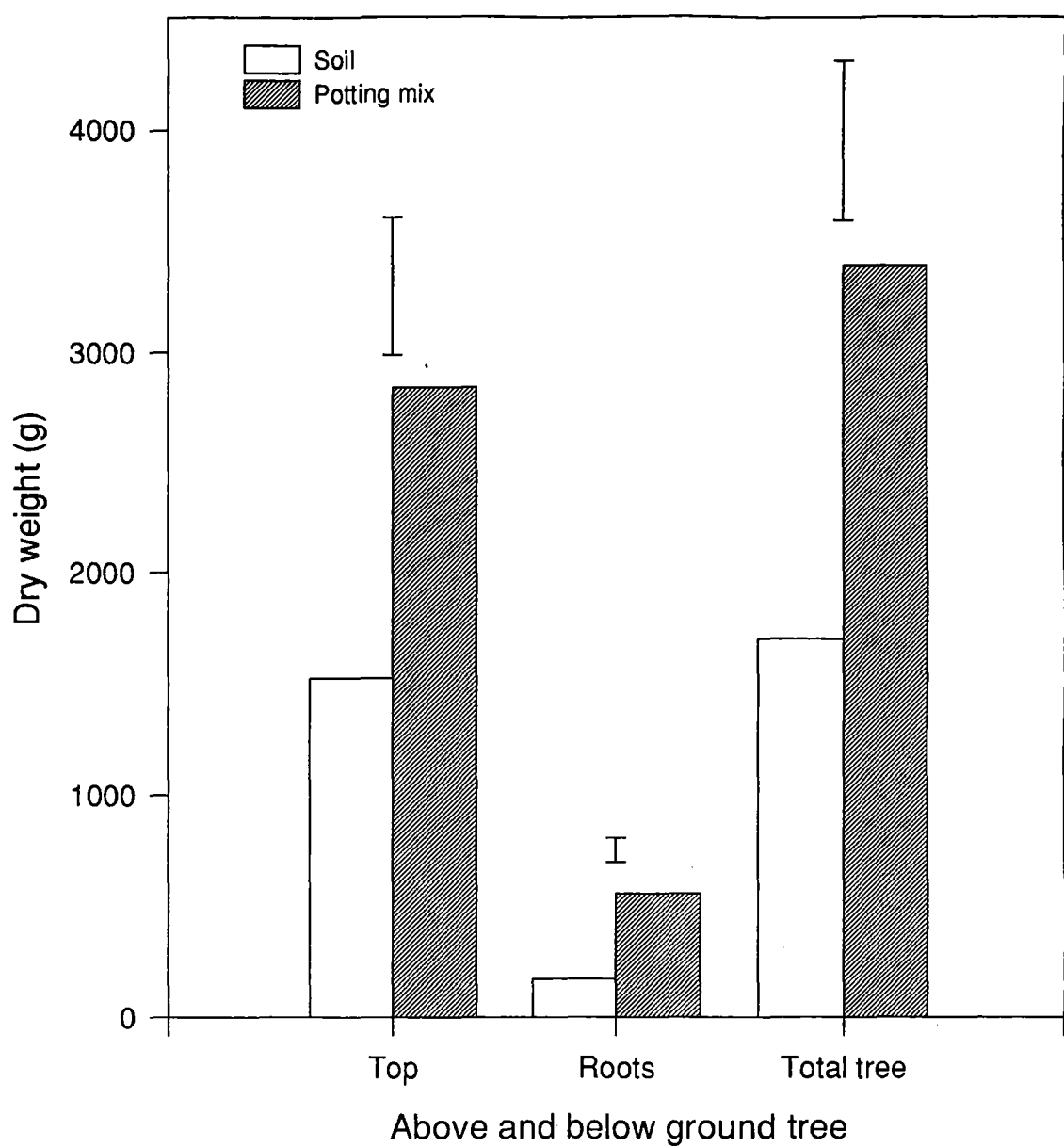


Figure 4.1.5. The effect of media on the dry weight of *Dodonaea* for all bag sizes after two years growth

Top	Tr Anova	P = 0.000
Roots	Tr Anova	P = 0.000
Total	Tr Anova	P = 0.000

LSD at 0.05 are represented by a capped vertical bar.

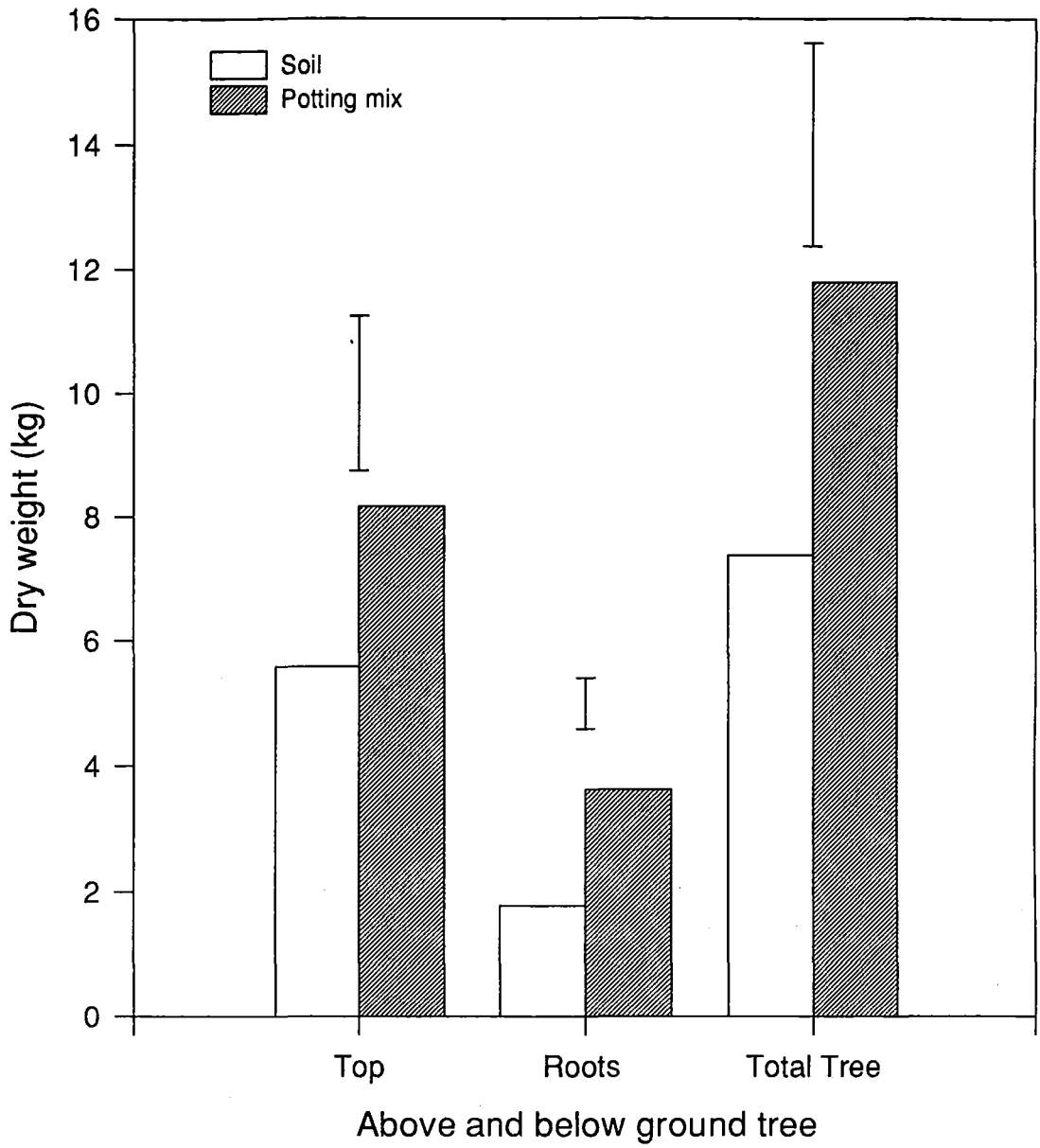


Figure 4.1.6. The effect of media on the dry weight of *Populus* after three years growth

Top Tr Anova $P = 0.044$

Roots Tr Anova $P = 0.000$

Total Tr Anova $P = 0.009$

LSD at 0.05 are represented by a capped vertical bar.

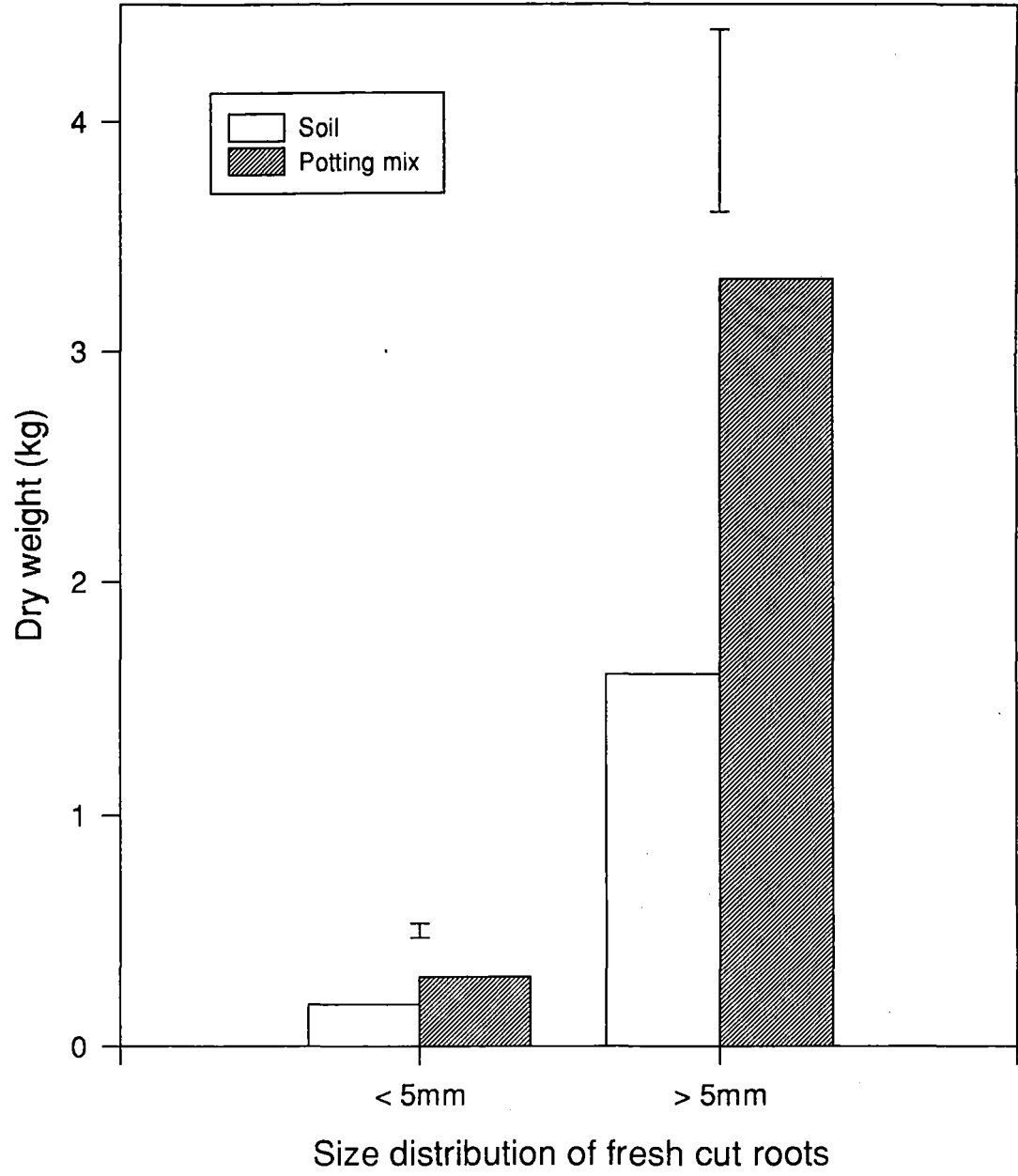


Figure 4.1.7. The effect of media on size distribution of *Populus* roots within bags after three years growth.

Roots >5 mm Tr Anova P = 0.001

Roots <5 mm Tr Anova P = 0.000

LSD at 0.05 are represented by a capped vertical bar.

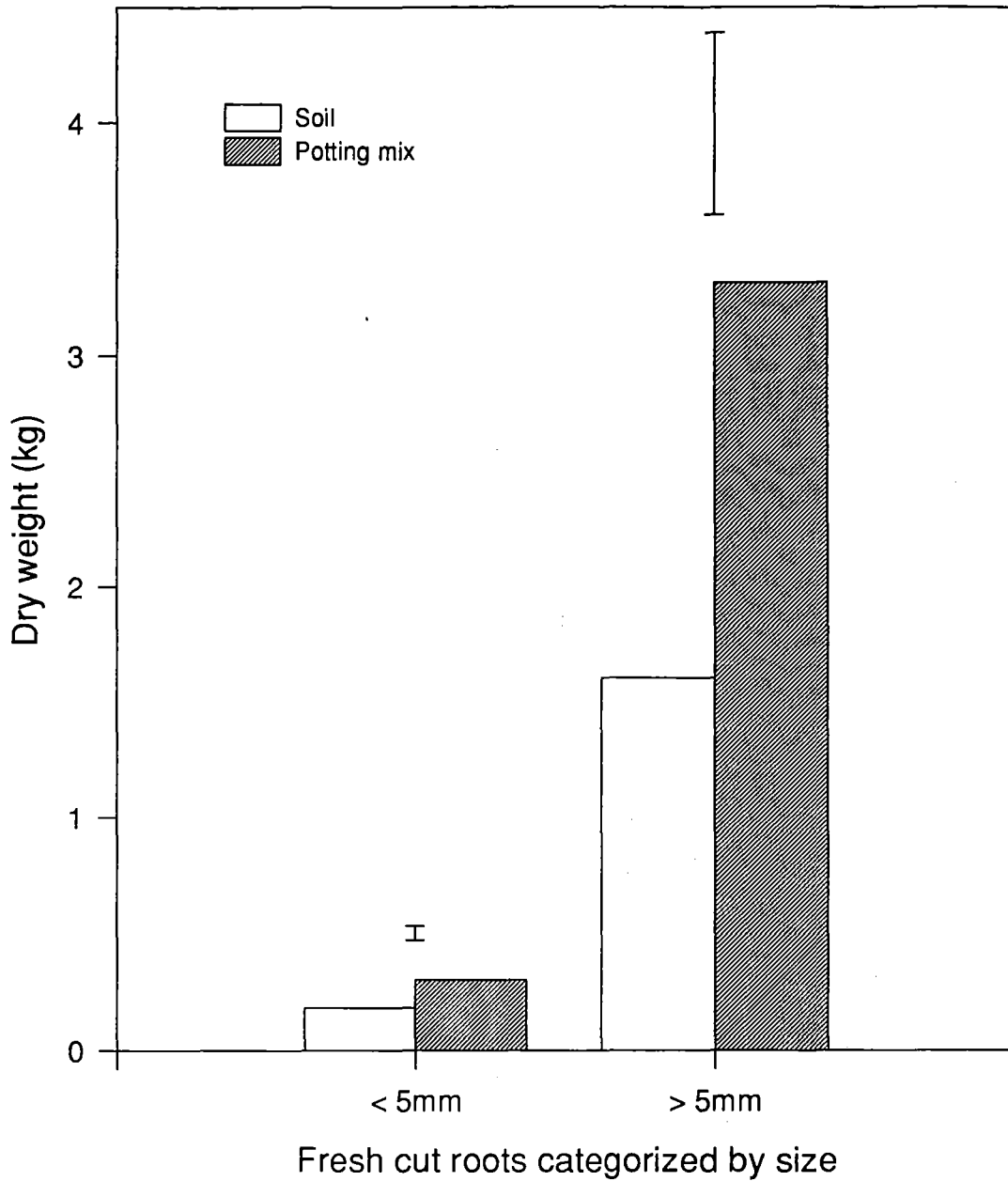


Figure 4.1.7. The effect of media on root size of *Populus* roots within bags after three years growth.

Roots >5 mm Tr Anova P = 0.001

Roots <5 mm Tr Anova P = 0.000

LSD at 0.05 are represented by a capped vertical bar.

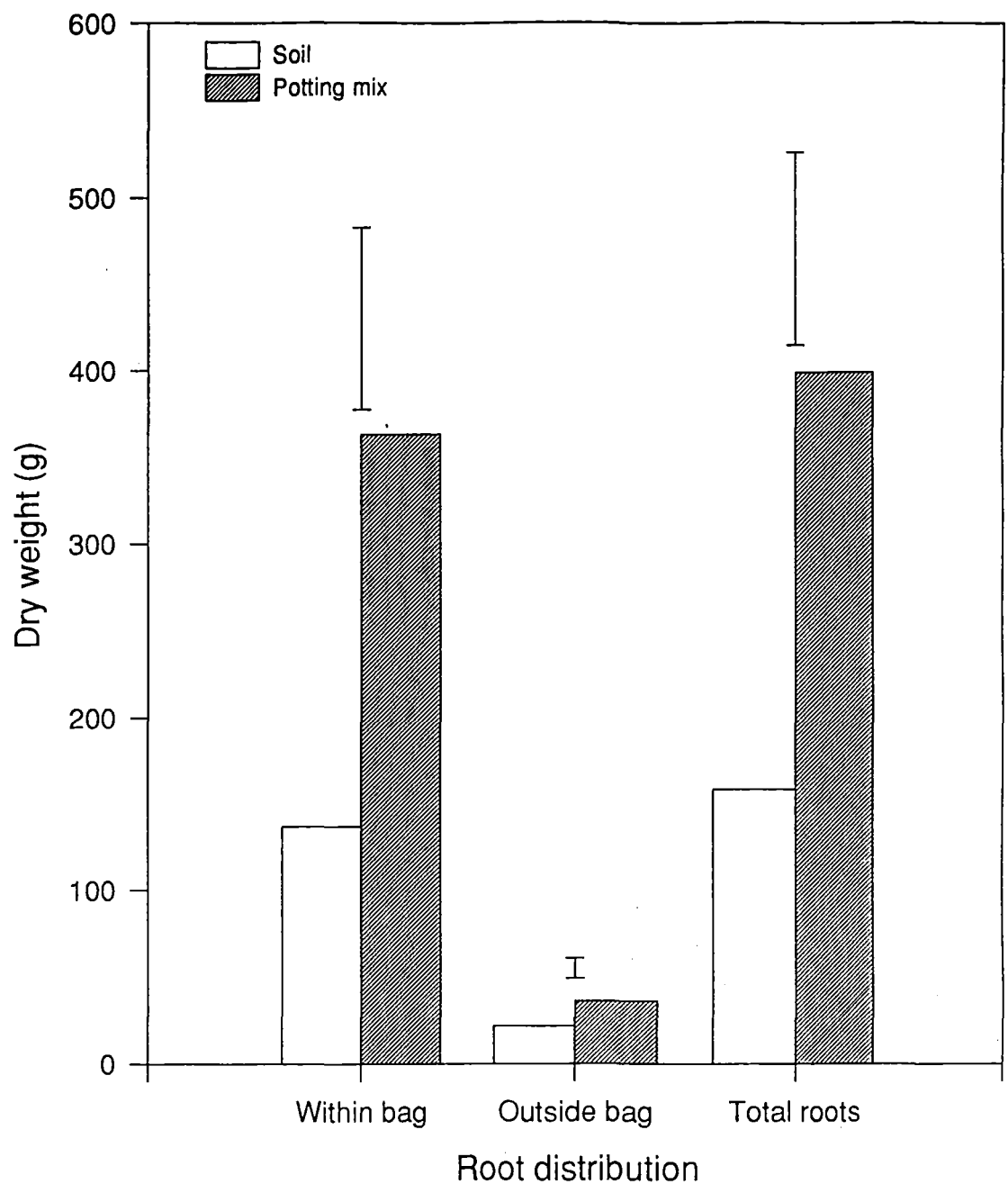


Figure 4.1.8. The effect of media on the root distribution dry weight of *Dodonaea* after two growing seasons. (two reps only)

Within bag	Tr Anova	P = 0.000
Outside bag	Tr Anova	P = 0.035
Total roots	Tr Anova	P = 0.000

LSD at 0.05 are represented by a capped vertical bar.

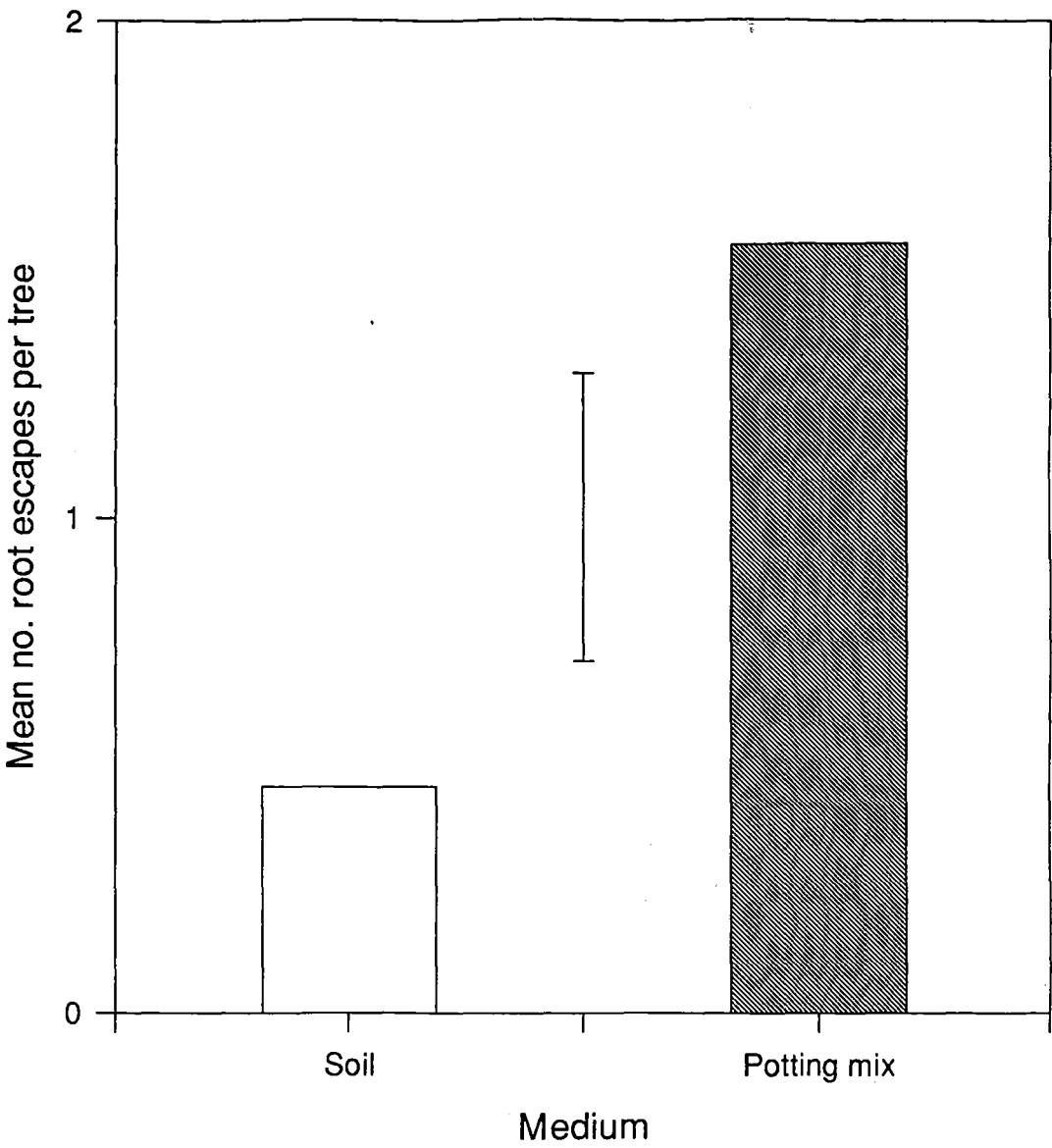


Figure 4.1.9. The effect of media on the number of root escapes per bag from *Populus* after three years growth.

Root escapes Tr Anova P = 0.001

LSD at 0.05 is represented by a capped vertical bar.

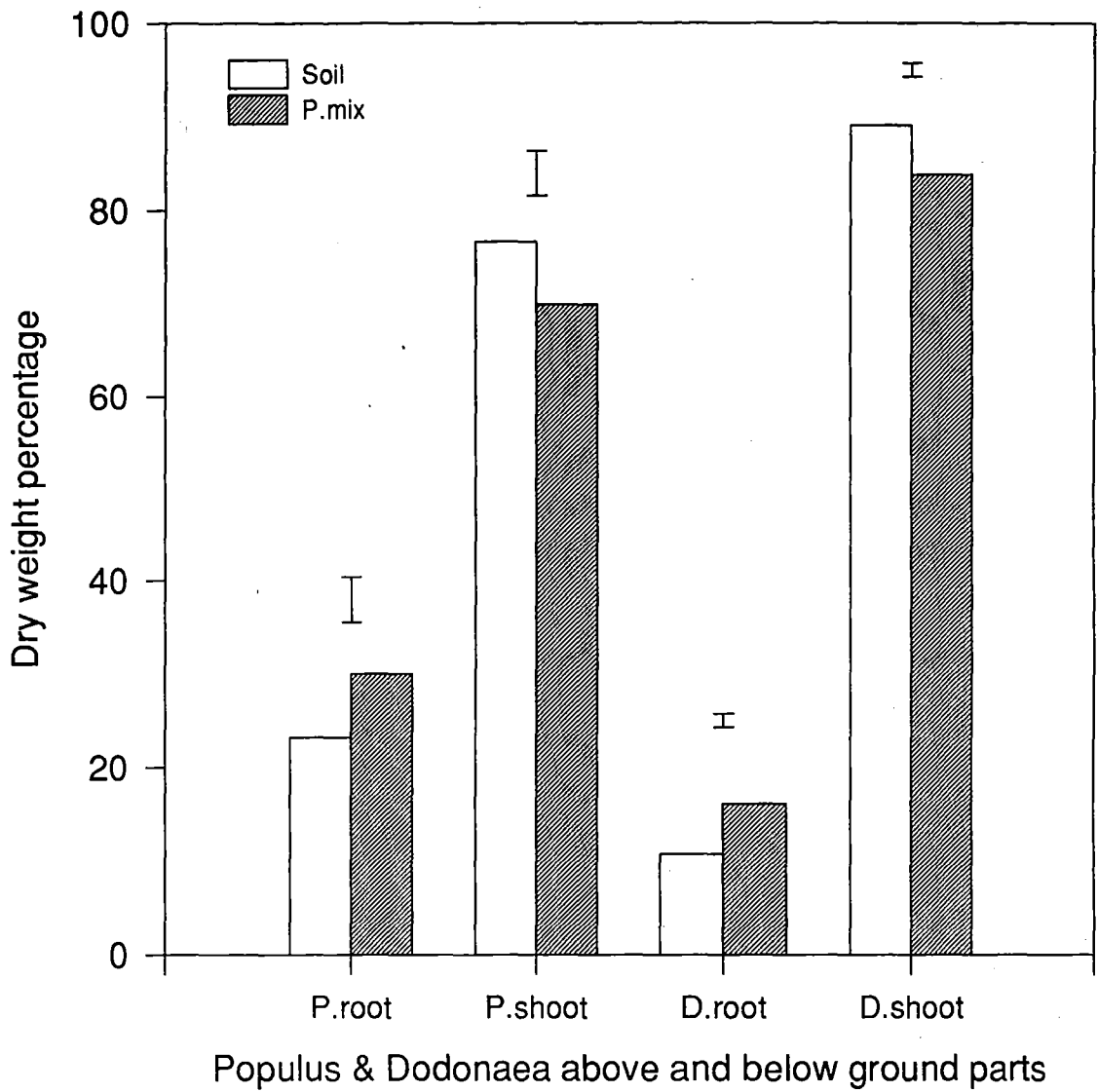


Figure 4.1.10. The effect of media on the relative root and shoot production for *Populus* after three years and *Dodonaea* after two years growth.

P root = *Populus* Root, P.shoot = *Populus* Shoot Tr Anova P = 0.008

D root = *Dodonaea* Root, D shoot = *Dodonaea* Shoot Tr Anova P = 0.000

LSD at 0.05 are represented by a capped vertical bar.

4.2.1. Effect of media on trees grown in 139 l bags and 139 l no bag (control)

4.2.2. Height

Dodonaea trees grown in 139 l bags and in control (139 l hole - no bag) grew taller in potting mix than trees in field soil in the first season. In the second season the increase in height of trees in soil approached significance. The cumulative effect of media for the first and second seasons growth showed trees grown in potting mix were taller than trees grown in field soil (Figure 4.2.1.). *Populus* trees also grew taller in the first season in potting mix. Measurements for the second and the third season showed no difference between the height of trees grown in potting mix or trees grown in field soil. The cumulative effect of media on the first and second seasons growth indicated trees grown in potting mix were taller than if grown in field soil. This was due to the effect of the faster growth in potting mix in the first season, however the cumulative effect of season one, two and three measured at the end of the third season showed no effect of media on the height of *Populus* trees (Figure 4.2.2.).

There were no significant interactions between media and bag v. no bag for either species of tree.

4.2.3. Trunk diameter

Both *Dodonaea* (Figure 4.2.3.), and *Populus* (Figure 4.2.4.) produced larger trunk diameters when grown in potting mix rather than field soil. There was no difference in trunk diameter increase in the second seasons growth for either species, the same result occurred for *Populus* in the third season as well. The cumulative effect of media for both species *Dodonaea* and *Populus* showed potting mix produced a larger trunk diameter than field soil after two seasons growth. The cumulative effect of season one, two and three on *Populus* trees showed the same trend with trees in potting mix with a larger trunk diameter than those grown in field soil. The main increase in trunk diameter occurred in the first seasons growth in potting mix.

There were no significant interactions between media and bag v. no bag for trunk diameter. *Populus* trees approached significance at the end of three seasons growth (Table 4.6.).

Table 4.6. Interaction between media and bag v. no bag on trunk diameter (mm) of *Populus* after three seasons growth

	Soil	Potting mix
Bag	46.14	58.04
No bag	81.06	71.49

P = 0.084

LSD = 8.45 (Level of significance .05)

4.2.4. *Populus* ‘Tasman’ fresh weight

The fresh weight of *Populus* trunk and branches measured at the end of three seasons growth showed a trend towards trees grown in potting mix being heavier than those grown in field soil. The fresh weight of roots was greater in trees grown in potting mix. (Figure 4.2.5.).

4.2.5. Dry weight

Dodonaea harvested after two years growth showed all measurements for both above ground and below ground level parts of the tree were heavier when grown in potting mix than when grown in soil (Figure 4.2.6.). *Populus* trees harvested after three years growth showed below ground level parts of the tree were heavier when grown in potting mix than when grown in soil. The above ground parts of the tree grown in potting mix or field soil were not significantly different, the total tree dry weight approached significance (Table 4.7.).

Table 4.7. Effect of media on dry weight (kg) of *Populus* after three seasons growth

Media	above ground tree	below ground	total tree
Soil	13.409	5.166 a	18.575
Potting mix	18.216	8.689 a	26.905
P =	0.186	0.02	0.101

LSD = 4.094 (Level of significance .05)

There were no significant interactions for dry weight between media and bag v. no bag.

4.2.6. Surface root crack length of *Populus* 'Tasman' after three seasons growth

There were no significant differences in surface root crack length between potting mix and field soil .

4.2.7. Relative root and shoot production

Media had a significant effect on the relative root and shoot production for both species; *Dodonaea* after two seasons and *Populus*, (Figure 4.2.7.), after three seasons growth. In both species the effect showed a higher proportion of root dry weight in trees grown in potting mix compared with trees grown in soil.

4.2.8. *Dodonaea viscosa* 'Purpurea' leaf colour

There was no effect based on leaf colour of *Dodonaea* for media in 139 litre bags and 139 litre no bag treatments.

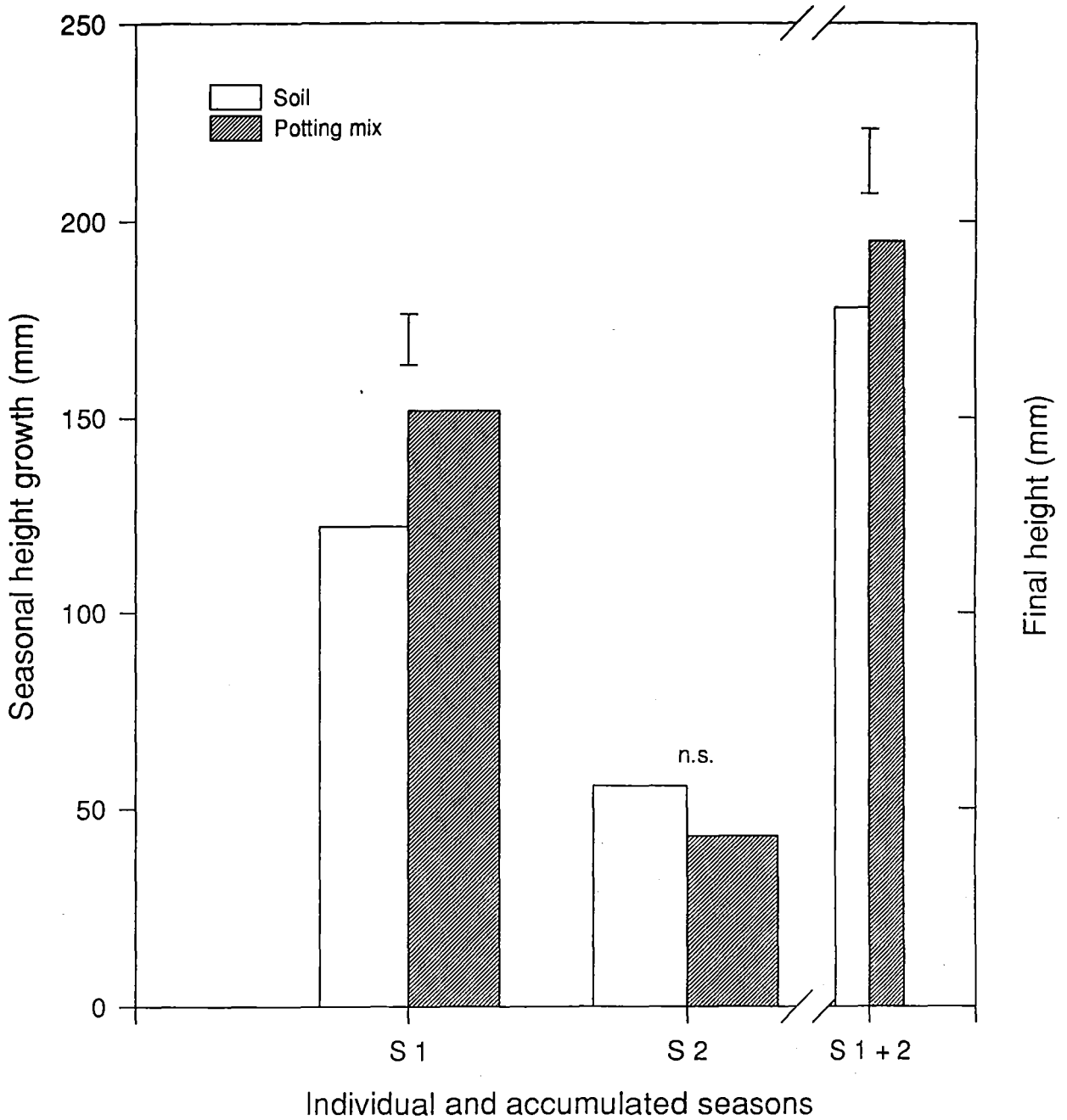


Figure 4.2.1. The effect of media on the seasonal increase and accumulated height of *Dodonaea* (means of 139 litre bag and 139 litre no bag treatments).

First season (S 1) Tr Anova P = 0.000

Second season (S 2) Tr Anova P = 0.053

Total of both seasons (S 1+2) Tr Anova P = 0.053

LSD at 0.05 are represented by a capped vertical bar.

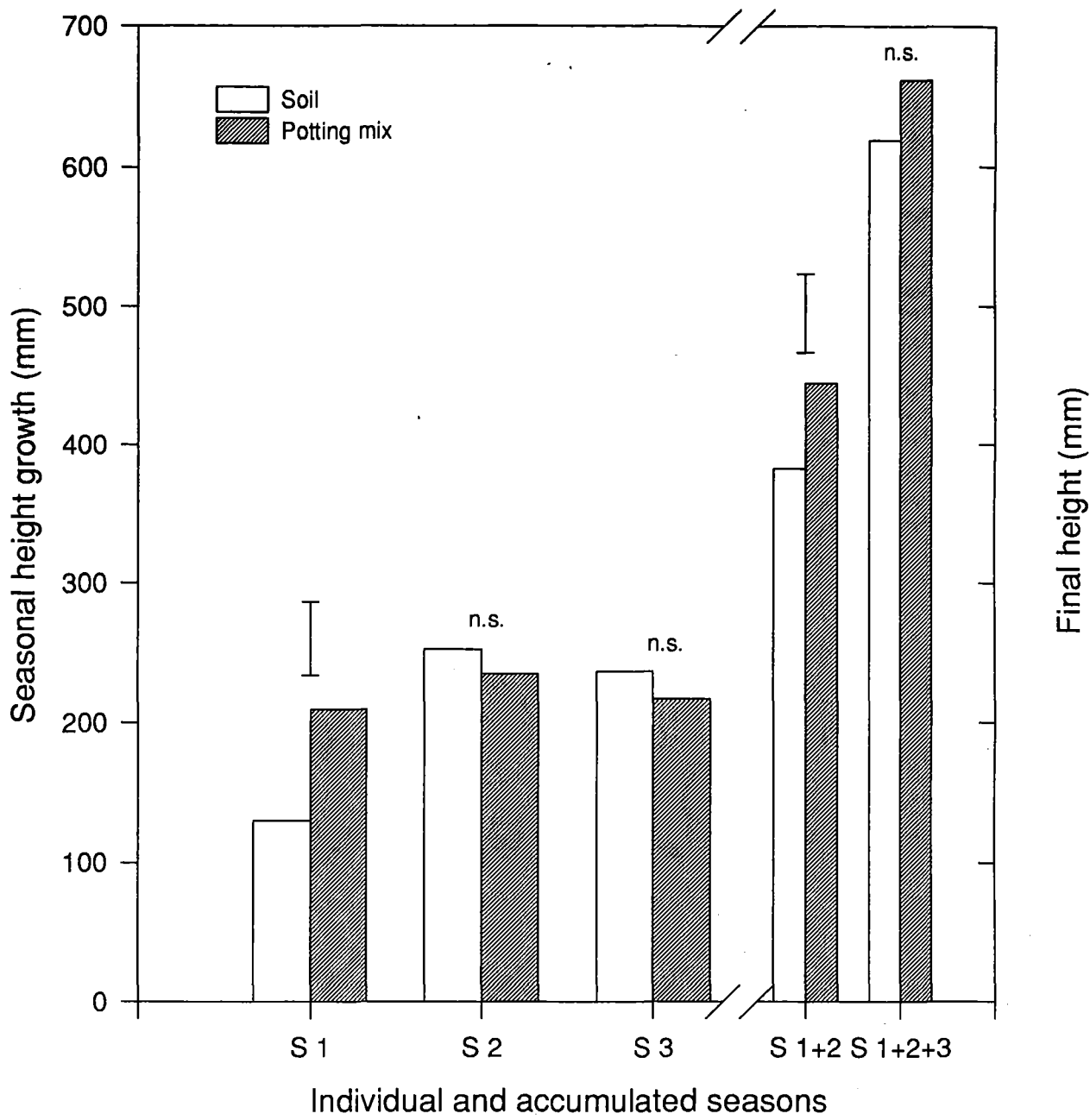


Figure 4.2.2. The effect of media on the seasonal increase and accumulated height of *Populus* (means of 139 litre bag and 139 litre no bag treatments).

First season	(S 1)	Tr Anova	P = 0.009
Second season	(S 2)	Tr Anova	P = 0.189
Third season	(S 3)	Tr Anova	P = 0.386
First & second season	(S 1+2)	Tr Anova	P = 0.041
Total of all seasons	(S 1+2+3)	Tr Anova	P = 0.142

LSD at 0.05 are represented by a capped vertical bar.

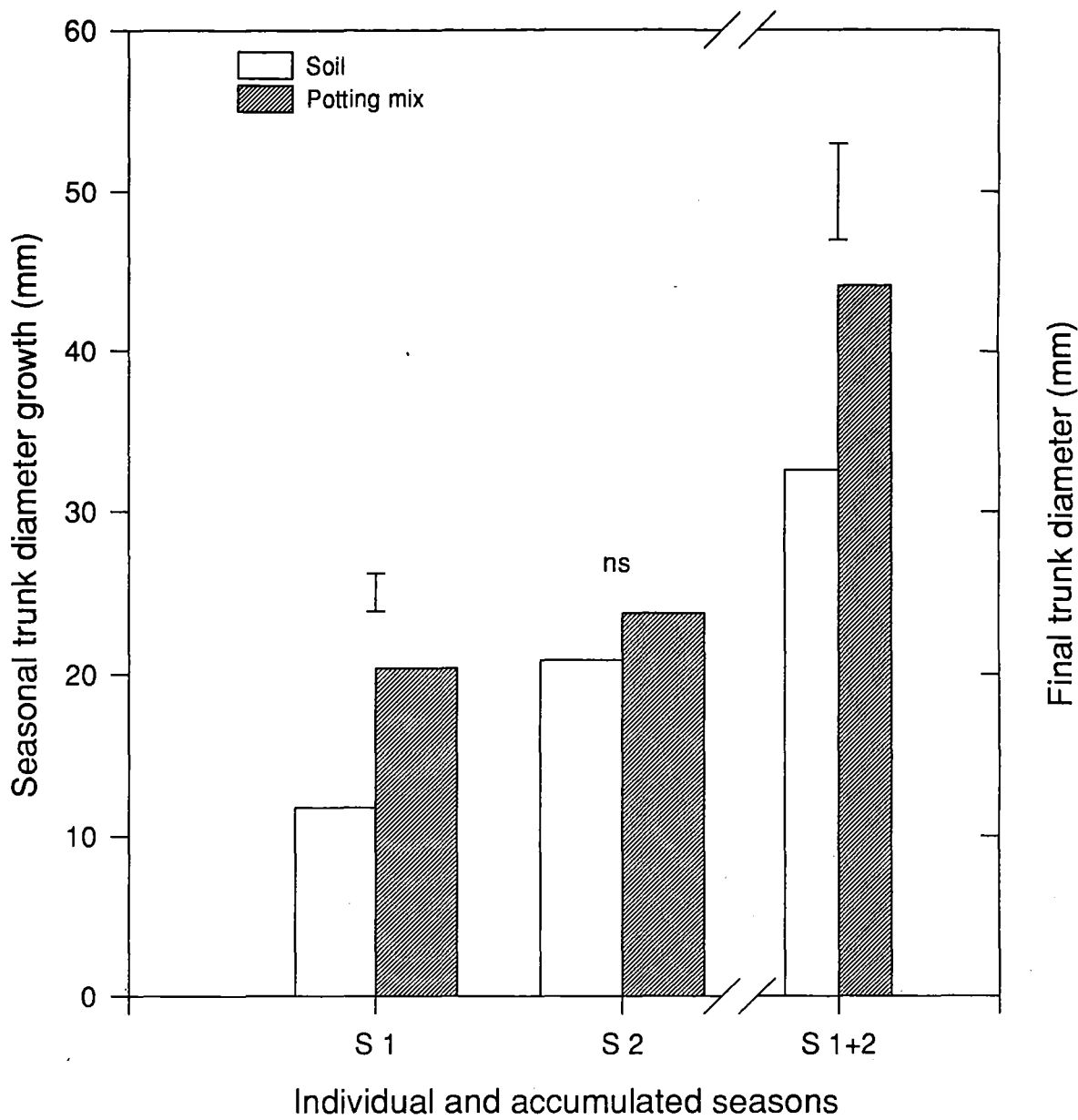


Figure 4.2.3. The effect of media on the seasonal increase and accumulated trunk diameter of *Dodonaea* (means of 139 litre bag and 139 litre no bag treatments).

First season	(S 1)	Tr Anova	P = 0.000
Second season	(S 2)	Tr Anova	P = 0.203
Total of both seasons	(S 1+2)	Tr Anova	P = 0.001

LSD at 0.05 are represented by a capped vertical bar.

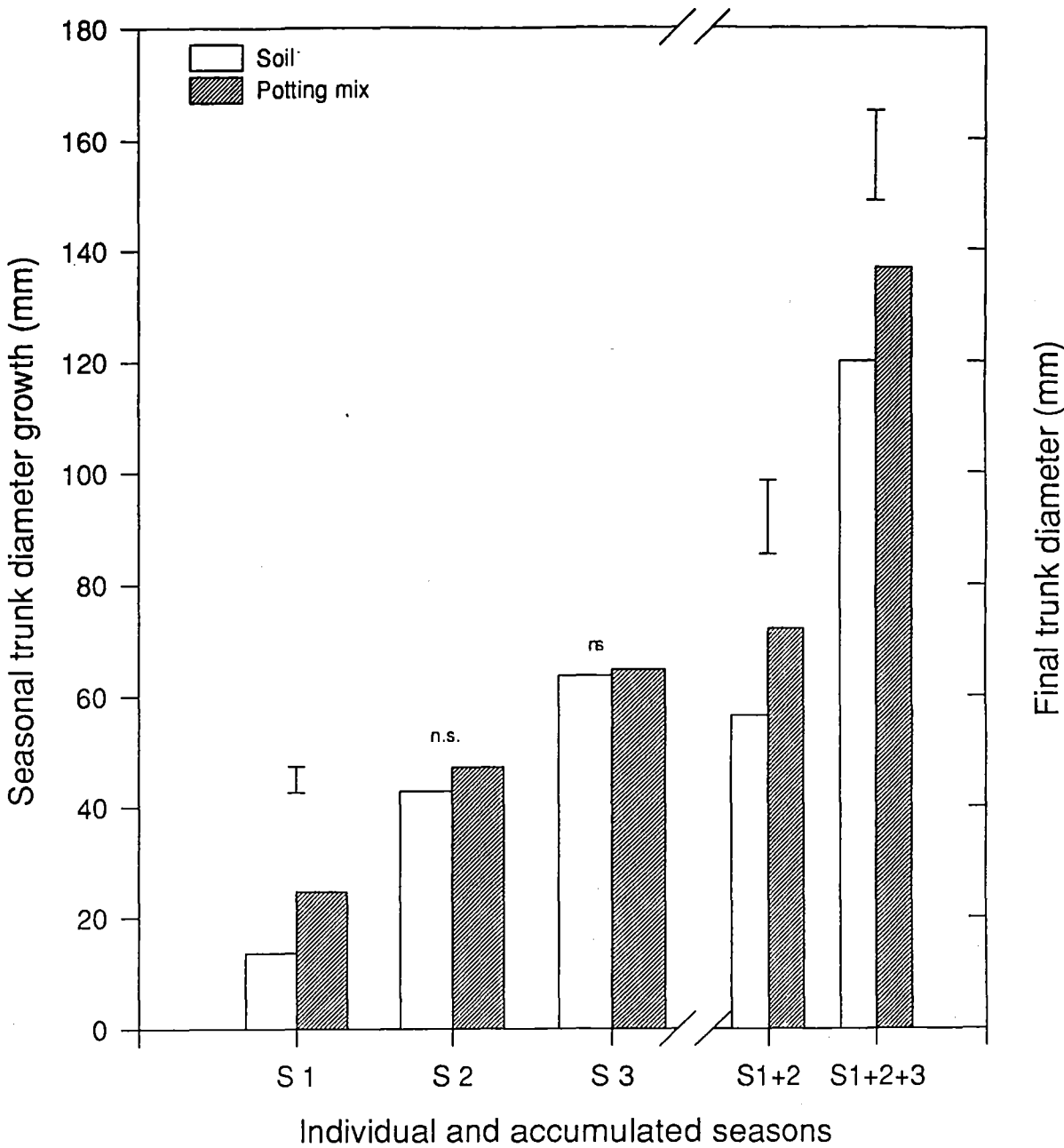


Figure 4.2.4. The effect of media on the seasonal increase and accumulated trunk diameter of *Populus* (means of 139 litre bag and 139 litre no bag treatments).

First season	(S 1)	Tr Anova	P = 0.000
Second season	(S 2)	Tr Anova	P = 0.334
Third season	(S 3)	Tr Anova	P = 0.841
First & second season	(S 1+2)	Tr Anova	P = 0.029
Total of all seasons	(S 1+2+3)	Tr Anova	P = 0.052

LSD at 0.05 are represented by a capped vertical bar.

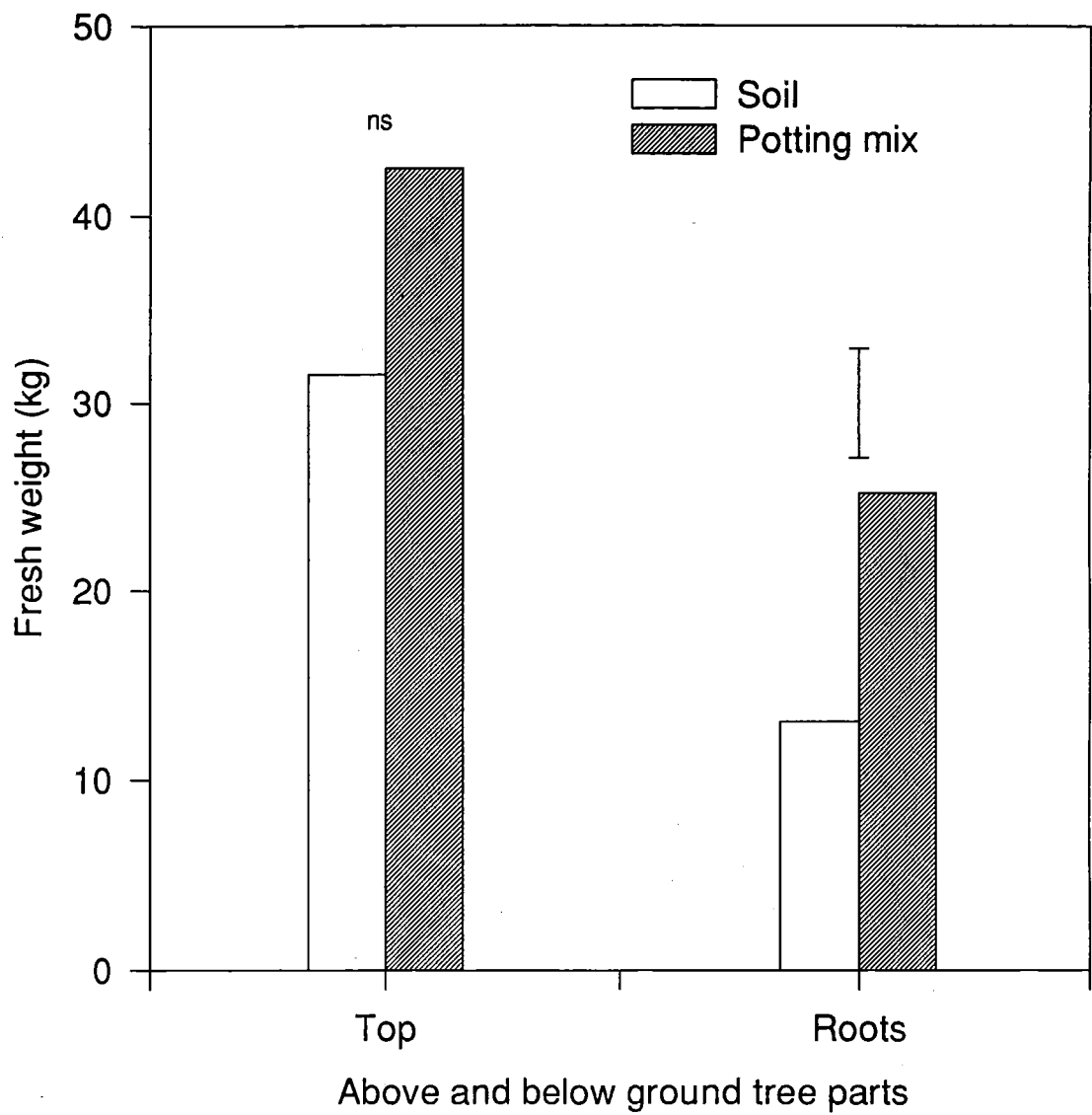


Figure 4.2.5. The effect of media on the fresh weight of *Populus* (means of 139 litre bag and 139 litre no bag treatments).

Top Tr Anova P = 0.063

Roots Tr Anova P = 0.000

LSD at 0.05 are represented by a capped vertical bar.

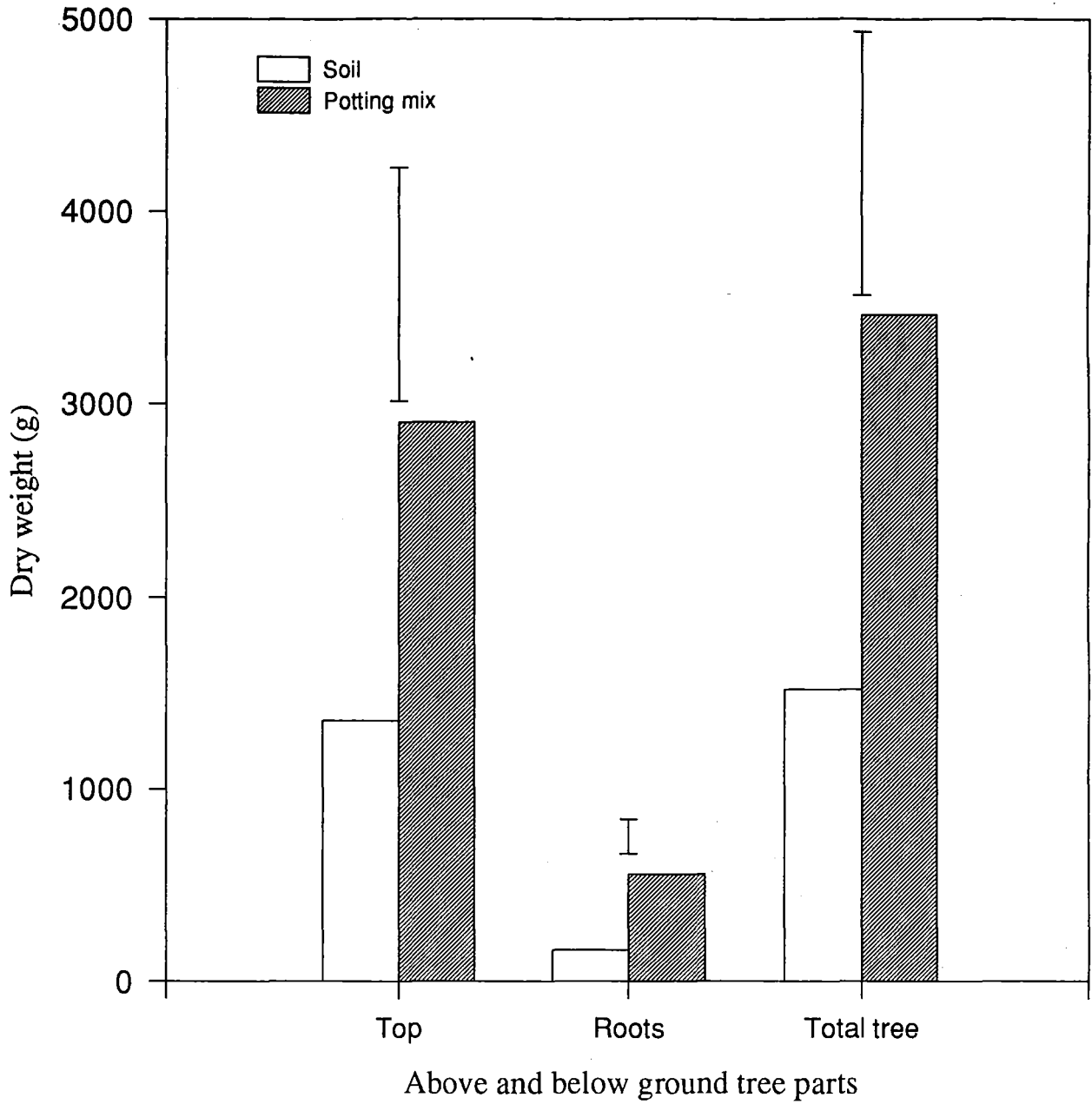


Figure 4.2.6. The effect of media on the dry weight of *Dodonaea* (means of 139 litre bag and 139 litre no bag treatments).

Top Tr Anova $P = 0.016$

Roots Tr Anova $P = 0.000$

Total Tr Anova $P = 0.010$

LSD at 0.05 are represented by a capped vertical bar.

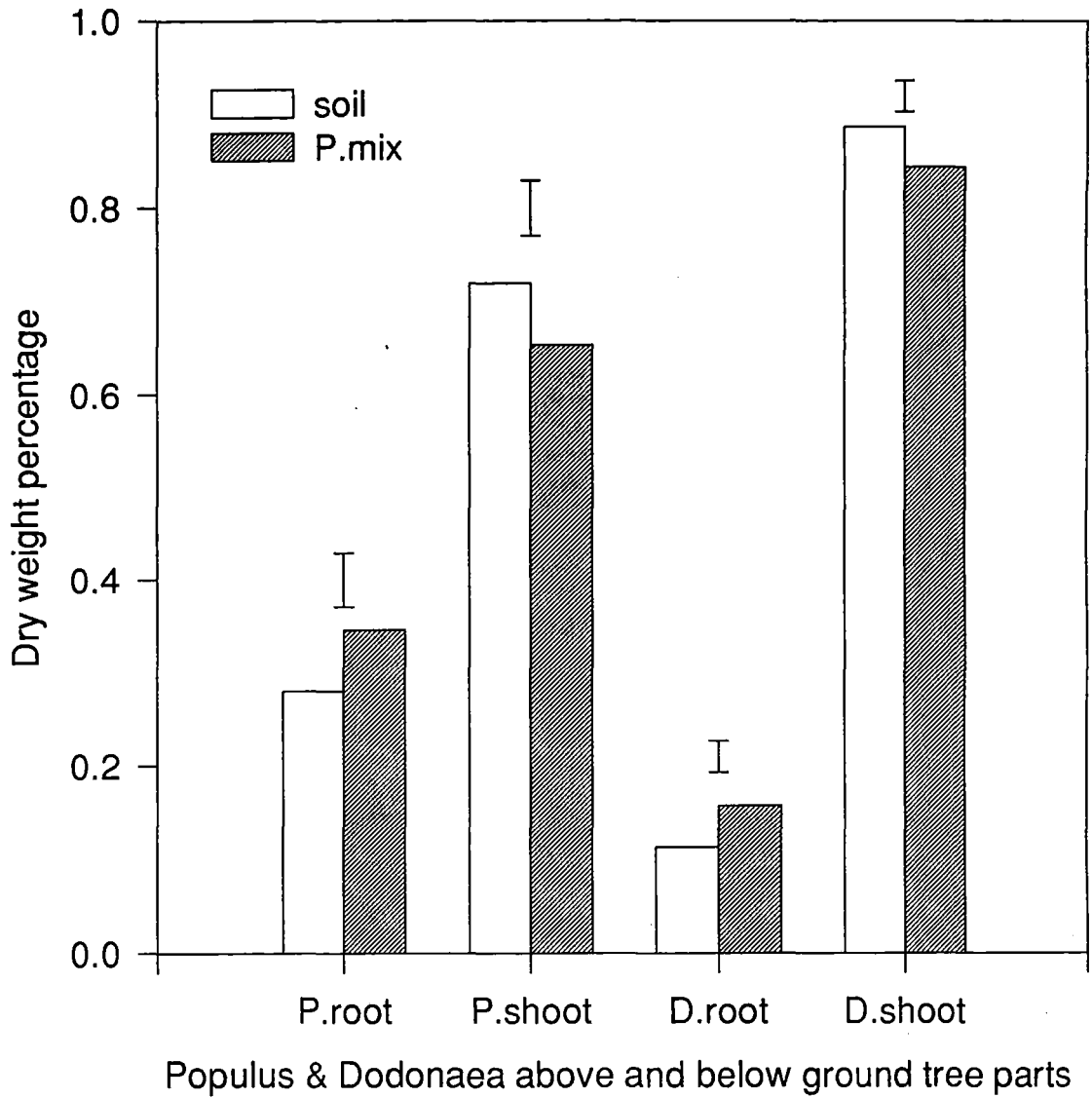


Figure 4.2.7. The effect of media on the relative root and shoot production for *Populus* and of *Dodonaea* (means of 139 litre bag and 139 litre no bag treatments).

Populus (after 3 seasons) Root : Shoot ratio Tr Anova P = 0.031

Dodonaea (after 2 seasons) Root : Shoot ratio Tr Anova P = 0.013

LSD at 0.05 are represented by a capped vertical bar.

4.3.1. Effect of bag volume on tree growth

4.3.2. Height

Bag volume had no effect on either *Dodonaea* or *Populus* for height in the first or second years growth. *Dodonaea* showed a trend for cumulative growth for years one and two, whilst the cumulative effect of three growing seasons for *Populus* was significant. The smallest bags restricting height the most, with the largest showing the least restriction (Figure 4.3.1.).

4.3.3. Trunk diameter

There was no effect of bag volume on trunk diameter in the first or second seasons growth for either species of tree. The cumulative effect of season one and two showed bag volume had no effect on trunk diameter for either species. The third seasons growth for *Populus* trees showed bag volume having an effect on trunk diameter. There was also a cumulative effect over three seasons growth by bag volume. A strong curvilinear effect was evident by the end of the third year with the smallest bag volume having the strongest effect on restricting trunk diameter (Figure 4.3.2.).

4.3.4. *Populus* 'Tasman' fresh weight

Fresh weight measured at the end of three seasons growth showed bag volume affected tree parts below and above ground level (Figure 4.3.3.). A strong linear trend was evident with smallest bags producing the smallest fresh weights to the largest bags producing the largest fresh weights.

4.3.5. Dry weight

There was no difference between dry weights for above ground tree parts for *Dodonaea* at the end of two seasons growth. Below ground parts based on bag volume approached significance. At the end of three seasons growth *Populus* showed that bag volume was having an effect on below ground level tree dry weight and above ground level tree dry

weight (Figure 4.3.4.). Below ground tree parts were separated while fresh into parts >5mm diameter and <5 mm diameter. The biggest effect was for roots > 5 mm diameter. Bag volume had a curvilinear effect on dry weights of both (Figure 4.3.5.). It is clear here that proportionately more secondary thickening has occurred in the larger bag sizes, relative to the proportion of smaller roots found.

4.3.6. Surface root crack length of *Populus* 'Tasman' after three seasons growth

Bag volume affected the degree to which surface root cracking was evident. The smallest bags produced the least through to the largest bags showing the greatest degree of surface root cracking (Figure 4.3.6.).

4.3.7. Root escapes after three seasons growth for *Populus* 'Tasman'

Bag volume indicated a trend approaching significance ($P=0.107$) with the largest bags allowing the greatest number of root escapes and the smallest bags the least number of escapes.

4.3.8. Root : shoot ratios

The root : shoot ratio for both *Dodonaea* after two seasons and for *Populus* at the end of three seasons growth showed an effect of bag volume (Figure 4.3.7.). As bag volume increased the root : shoot ratio also increased for both species. The slope of the line was significantly greater for *Populus*. This is a reflection of the extra seasons growth and the greater time roots have had to fill the smaller bag sizes. From this result it is apparent that in the smaller bags after sufficient time for the trees to grow that allocation of carbohydrate for storage in the root and root growth is more difficult than where there is still adequate space for root growth in the larger bags

4.3.9. *Dodonaea viscosa* 'Purpurea' leaf colour

There was no effect based on leaf colour of *Dodonaea* and bag volume.

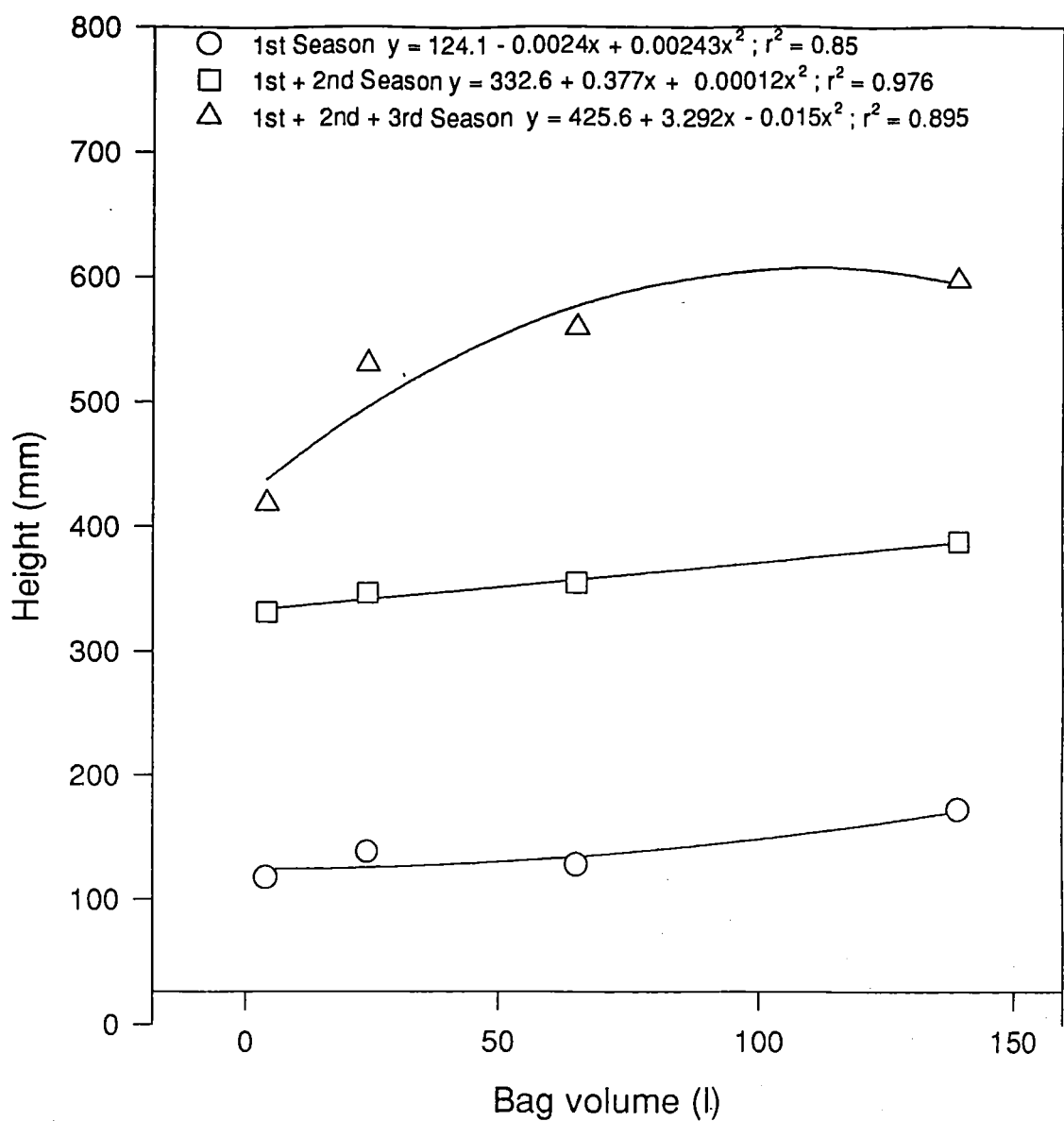


Figure 4.3.1. The effect of bag volume on *Populus* tree height at the end of the first, second and third seasons growth.

First season	Tr Anova	P = 0.231
First & second season	Tr Anova	P = 0.349
Total of all seasons	Tr Anova	P = 0.006

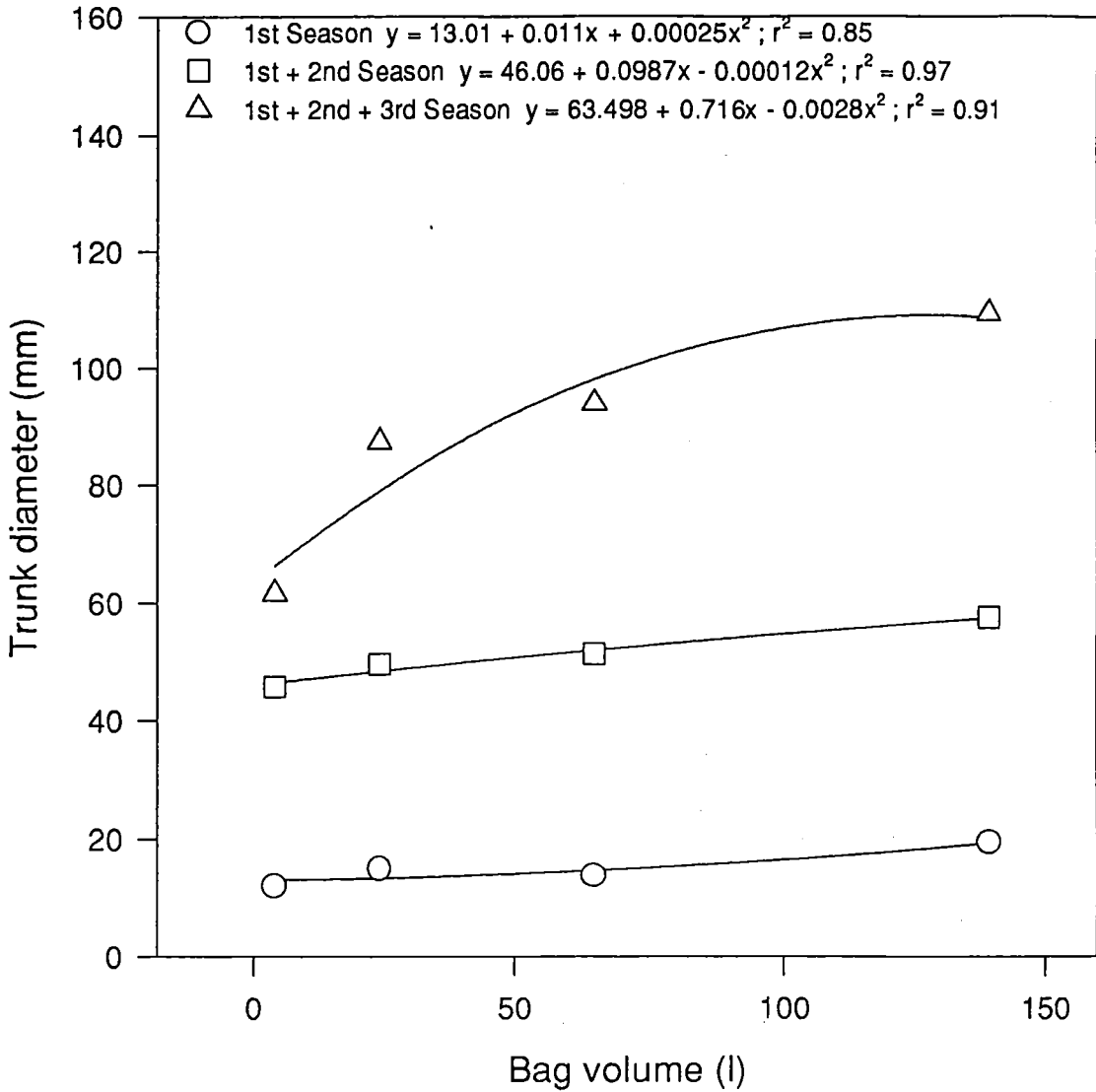


Figure 4.3.2. The effect of bag volume on trunk diameter of *Populus* at the end of the first, second and third growing season.

Year 1	Tr Anova	P = 0.063
Year 1+2	Tr Anova	P = 0.176
Year 1+2+3	Tr Anova	P = 0.000

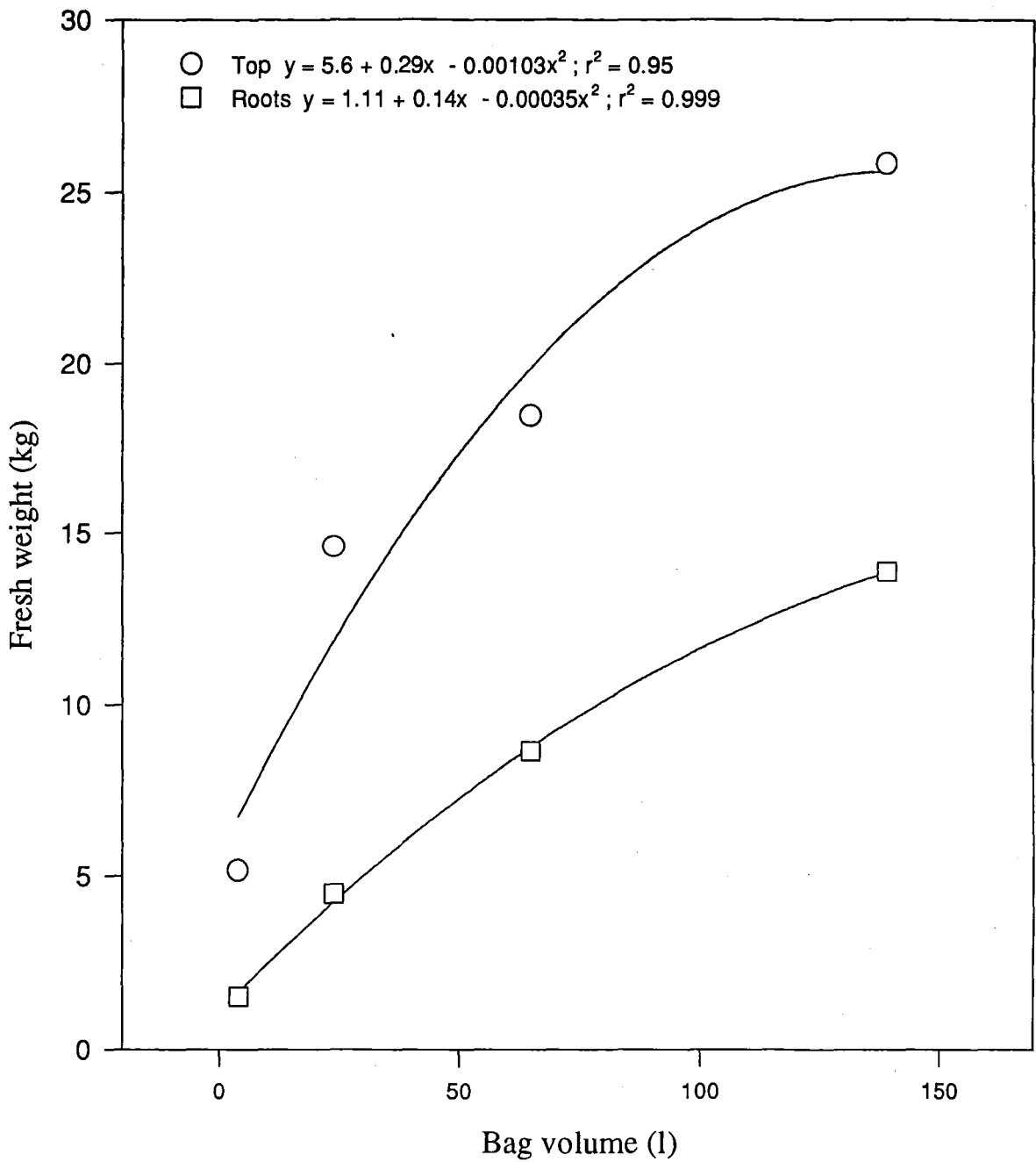


Figure 4.3.3. The effect of bag volume on the top and root fresh weight of *Populus* after three seasons growth.

Top Tr Anova $P = 0.000$

Roots Tr Anova $P = 0.000$

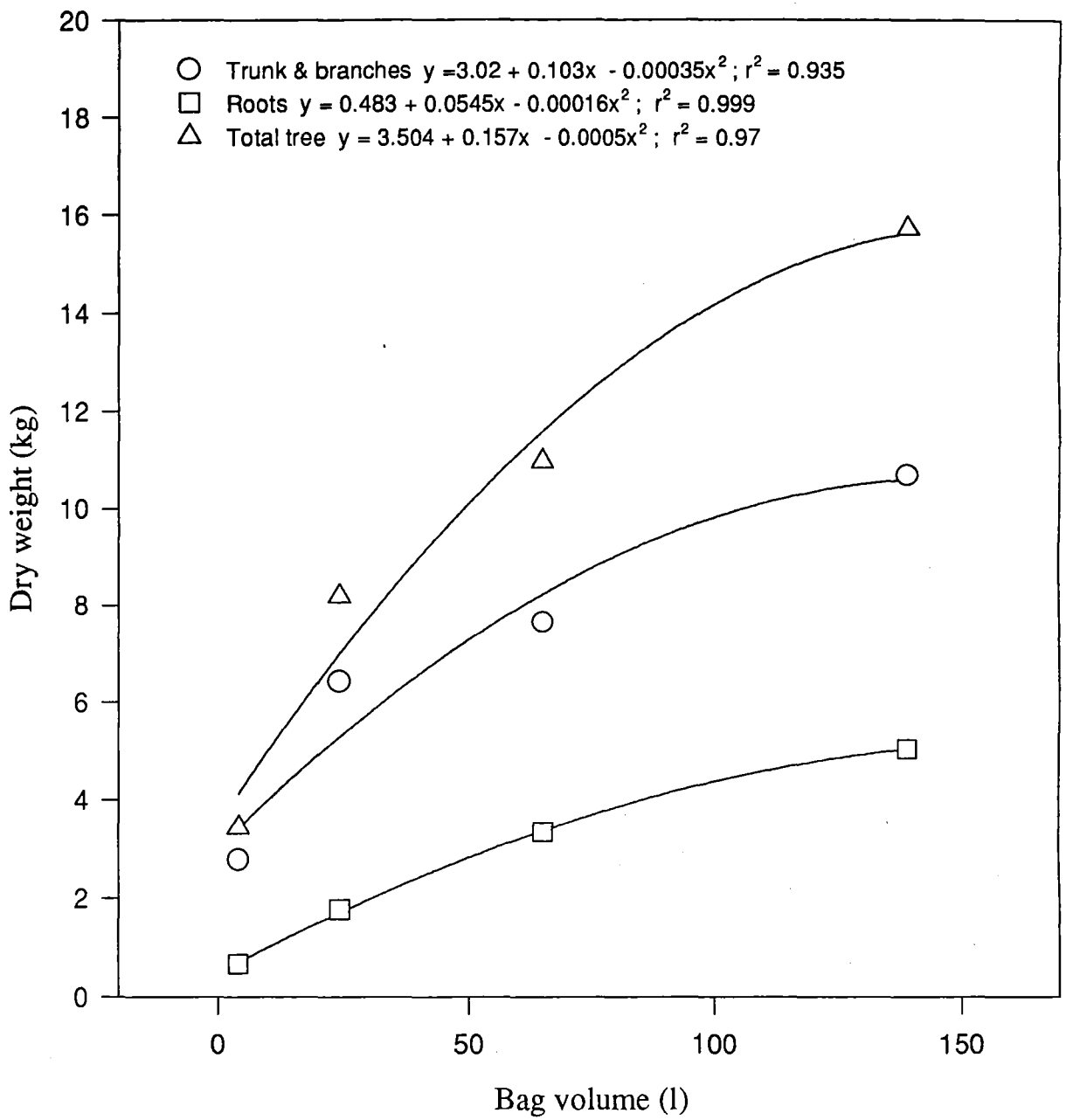


Figure 4.3.4. The effect of bag volume on the dry weight of *Populus* after three seasons growth.

Top	Tr Anova	P = 0.001
Roots	Tr Anova	P = 0.000
Total	Tr Anova	P = 0.000

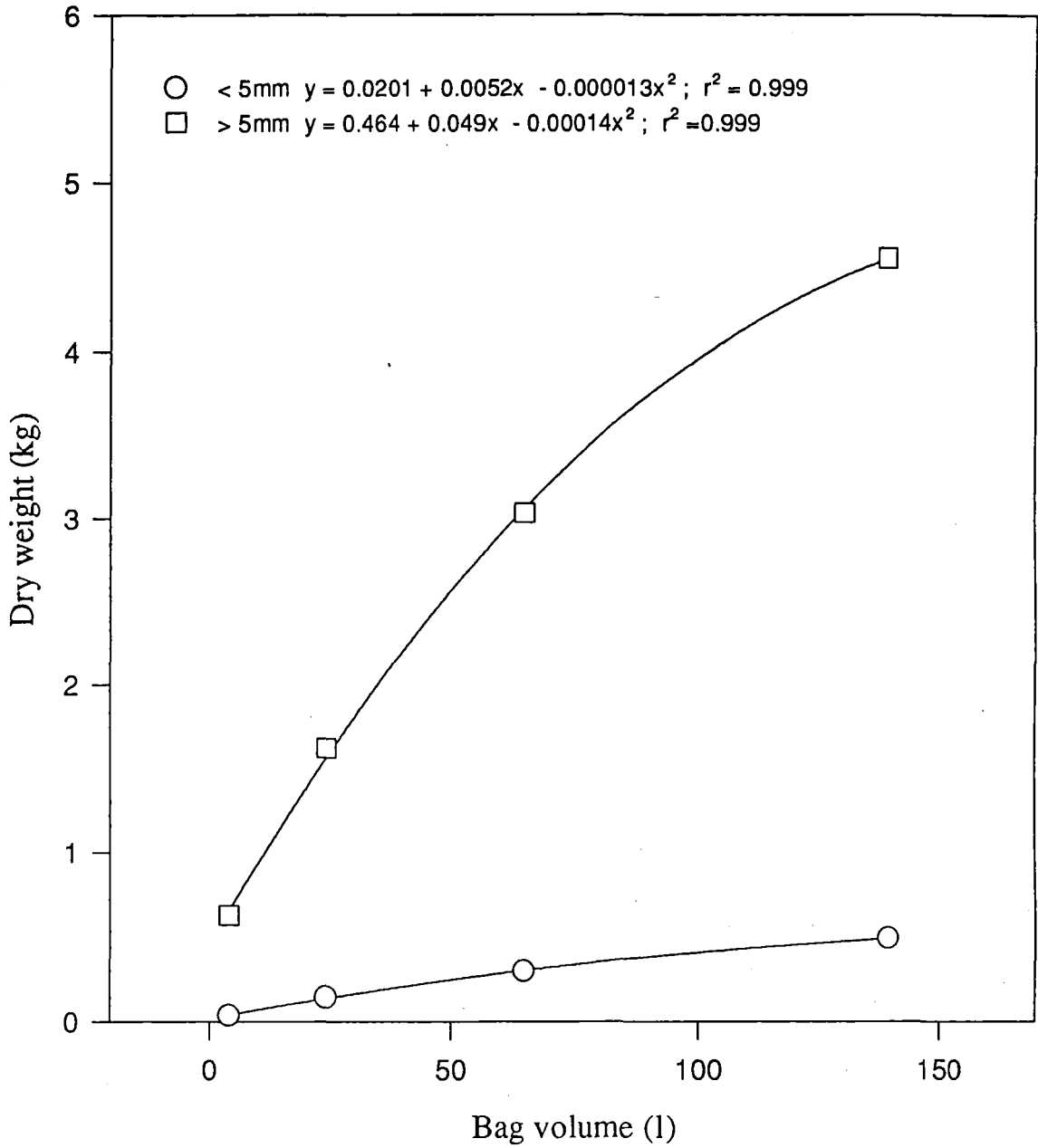


Figure 4.3.5. The effect of bag volume on the size categorization of *Populus* roots (fresh before drying) after three seasons growth.

Roots >5 mm Tr Anova P = 0.000

Roots <5 mm Tr Anova P = 0.000

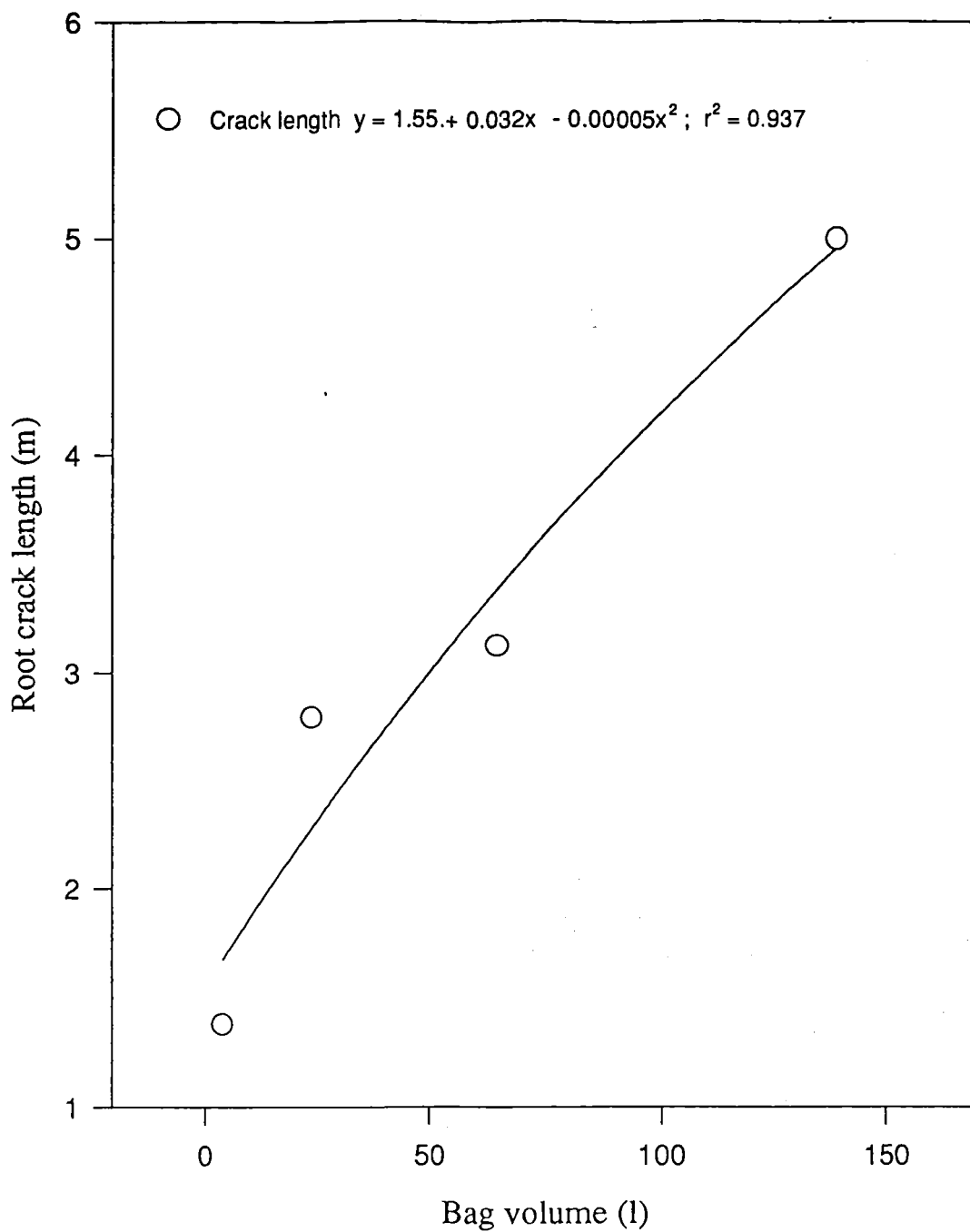


Figure 4.3.6. The effect of bag volume on the mean length of surface root cracks radiating out from the bags of *Populus* after three seasons growth.

Root crack length Tr Anova $P = 0.019$

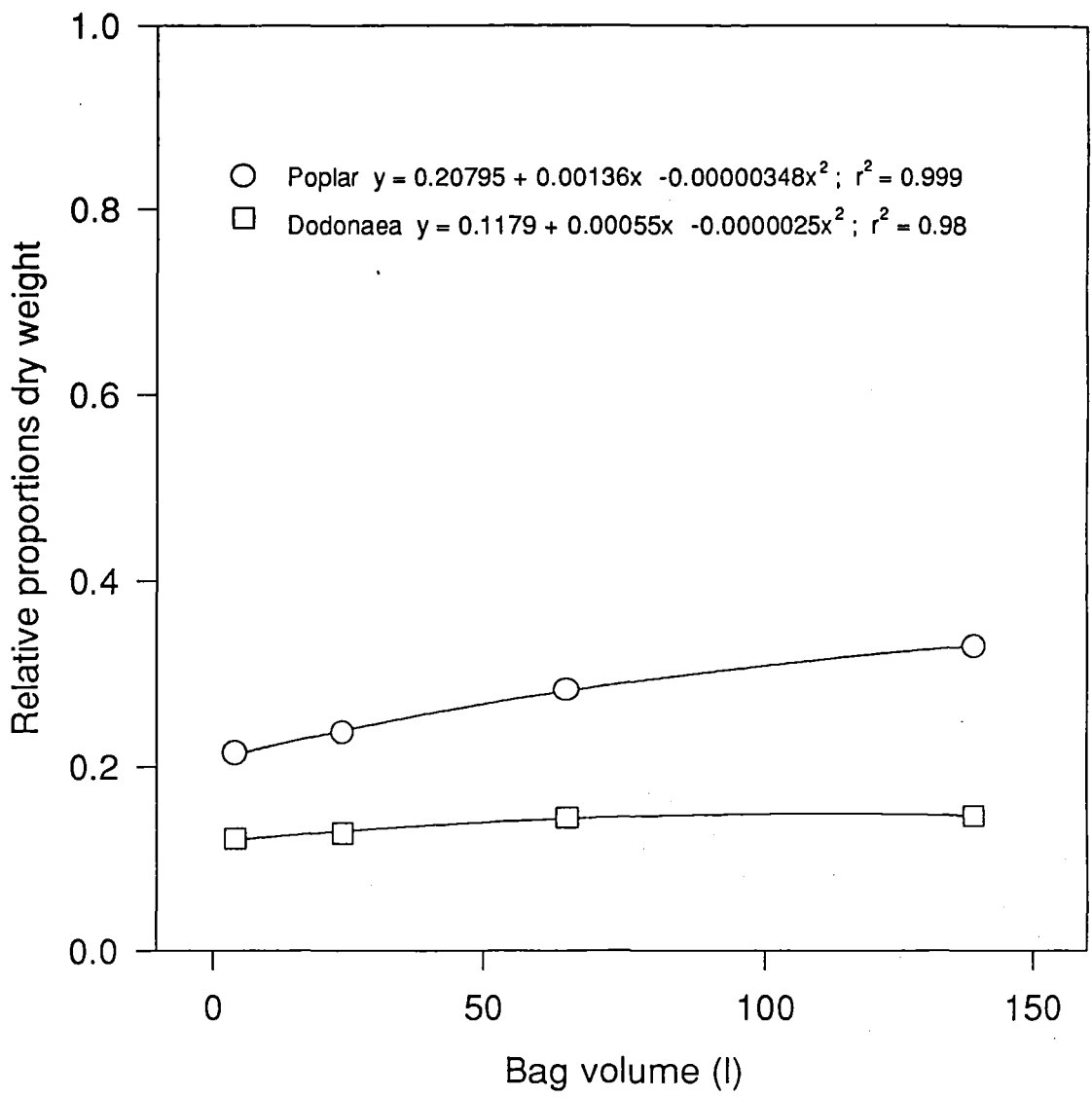


Figure 4.3.7. Root : Shoot ratios for *Dodonaea* and *Populus*

Dodonaea after two seasons growth Root : Shoot ratio Tr Anova P = 0.046

Populus after three seasons growth Root : Shoot ratio Tr Anova P = 0.008

4.4.1. Effect of 139 litre bag and 139 litre no bag (control) on tree growth

4.4.2. Height

There was no significant difference in height for either species at the end of the first growing season for 139 litre bagged or 139 litre non bagged trees. *Dodonaea* trees showed no difference between treatments for the second seasons growth either. *Populus* trees for both the second and third seasons growth showed trees growing in no bag treatments were taller on average (Figure 4.4.1.).

The cumulative effect of seasons one plus two for bag versus no bag treatments for *Dodonaea* showed there was no treatment effect on height, while *Populus* trees showed a trend toward trees in no bag treatments being taller than trees grown within bags. The cumulative effect of bag versus no bag treatments for *Populus* at the end of three seasons growth showed trees were shorter when grown in geotextile bags.

4.4.3. Trunk diameter

By the end of the first growing season there was no effect on trunk diameter for either species between trees grown in 139 litre bag or 139 litre no bag. In the second seasons growth *Dodonaea* showed a trend toward trunk diameter being smaller in bagged trees, while *Populus* trees showed a treatment difference with trunk diameter being smaller for trees grown in bagged treatments for both second and third seasons growth.

The cumulative effect of seasons one plus two for bag versus no bag treatments for *Dodonaea* showed there was no treatment effect on trunk diameter, but *Populus* indicated a treatment effect of the bag restricting trunk diameter. The cumulative effect of bag versus no bag treatments for *Populus* at the end of three seasons growth showed trees in bags were progressively more restricted and this was limiting trunk diameter (Figure 4.4.2.).

4.4.4. Populus fresh weight

The fresh weight of trunk and branches showed trees grown in bags weighed less than trees in the no bag treatments. The fresh weight of roots harvested also showed the same treatment effect as above (Figure 4.4.3.).

4.4.5. Dry weight

Dry weight measurements of *Dodonaea* after two seasons growth showed no difference between treatments, the dry weight of roots indicated a trend only toward roots in bag treatments being less than no bag treatments. The dry weights for *Populus* trees after three seasons growth showed trees grown in bags produced less dry weight than trees in no bag treatments - for above ground tree, below ground level tree and the total tree (Figure 4.4.4.).

4.4.6. Surface root crack length for Populus

The length of surface root length cracks measured toward the end of the third seasons growth showed trees in 139 litre no bags produced more cracking than trees in 139 litre bagged treatments (Figure 4.4.5.).

4.4.7. Root : shoot ratios

There was no effect of the 139 litre bag versus the 139 litre no bag treatments on the root : shoot ratios for *Dodonaea* after two seasons growth or for *Populus* trees after three seasons growth.

4.4.8. *Dodonaea viscosa* 'Purpurea' leaf colour

There was no effect of leaf colour and 139 litre bag and 139 litre no bag treatments for *Dodonaea*.

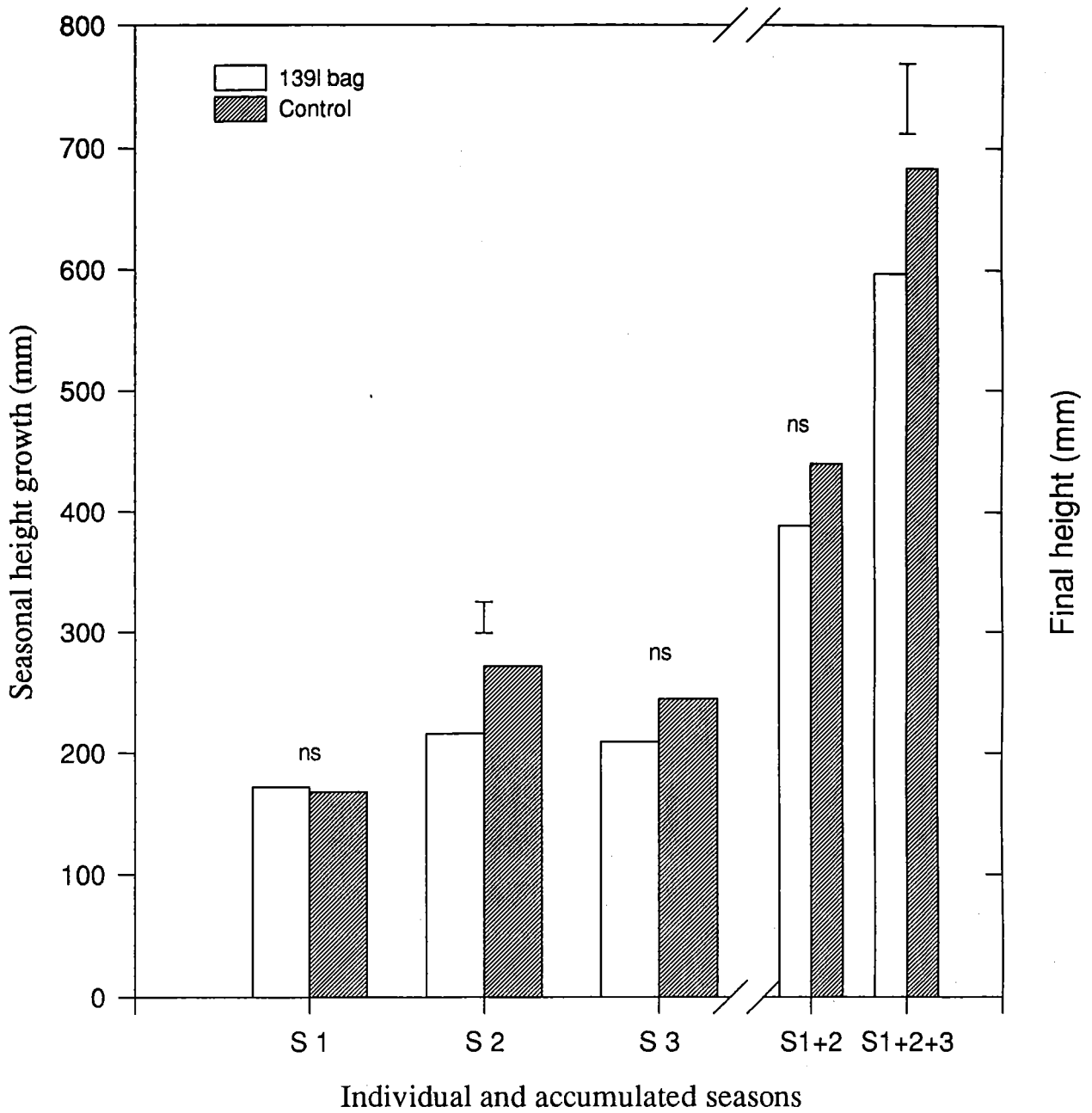


Figure 4.4.1. The effect of 139 litre bag and 139 litre no bag treatments on the height increase of *Populus* for individual and accumulated seasons growth.

First season	(S 1)	Tr Anova	P = 0.875
Second season	(S 2)	Tr Anova	P = 0.000
Third season	(S 3)	Tr Anova	P = 0.129
First & second season	(S1+2)	Tr Anova	P = 0.081
Total of all seasons	(S1+2+3)	Tr Anova	P = 0.008

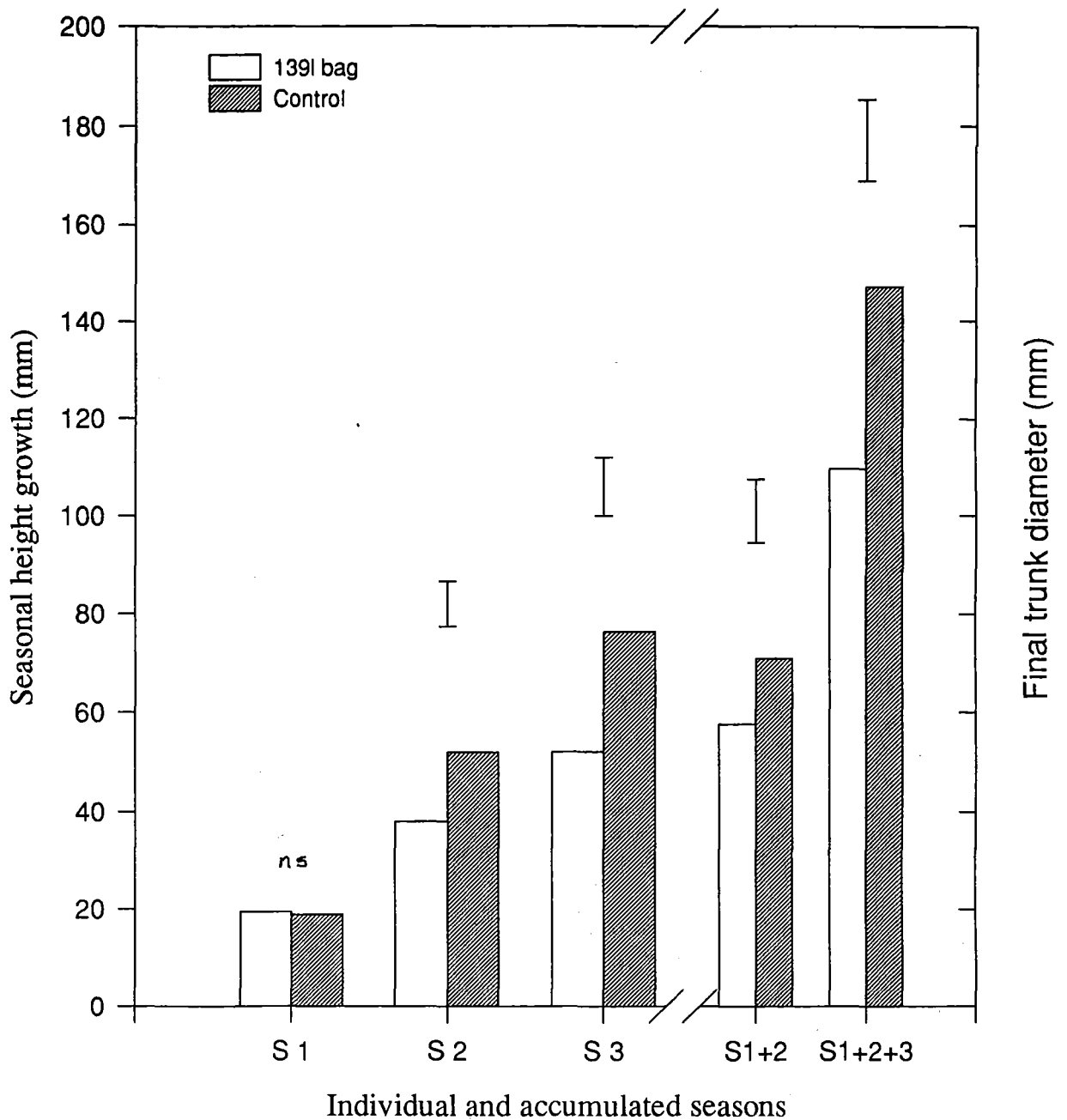


Figure 4.4.2. The effect of 139 litre bag and 139 litre no bag treatments on the trunk diameter of *Populus* for individual and accumulated seasons growth.

First season	(S 1)	Tr Anova	P = 0.802
Second season	(S 2)	Tr Anova	P = 0.009
Third season	(S 3)	Tr Anova	P = 0.001
First & second season	(S1+2)	Tr Anova	P = 0.054
Total of all seasons	(S1+2+3)	Tr Anova	P = 0.000

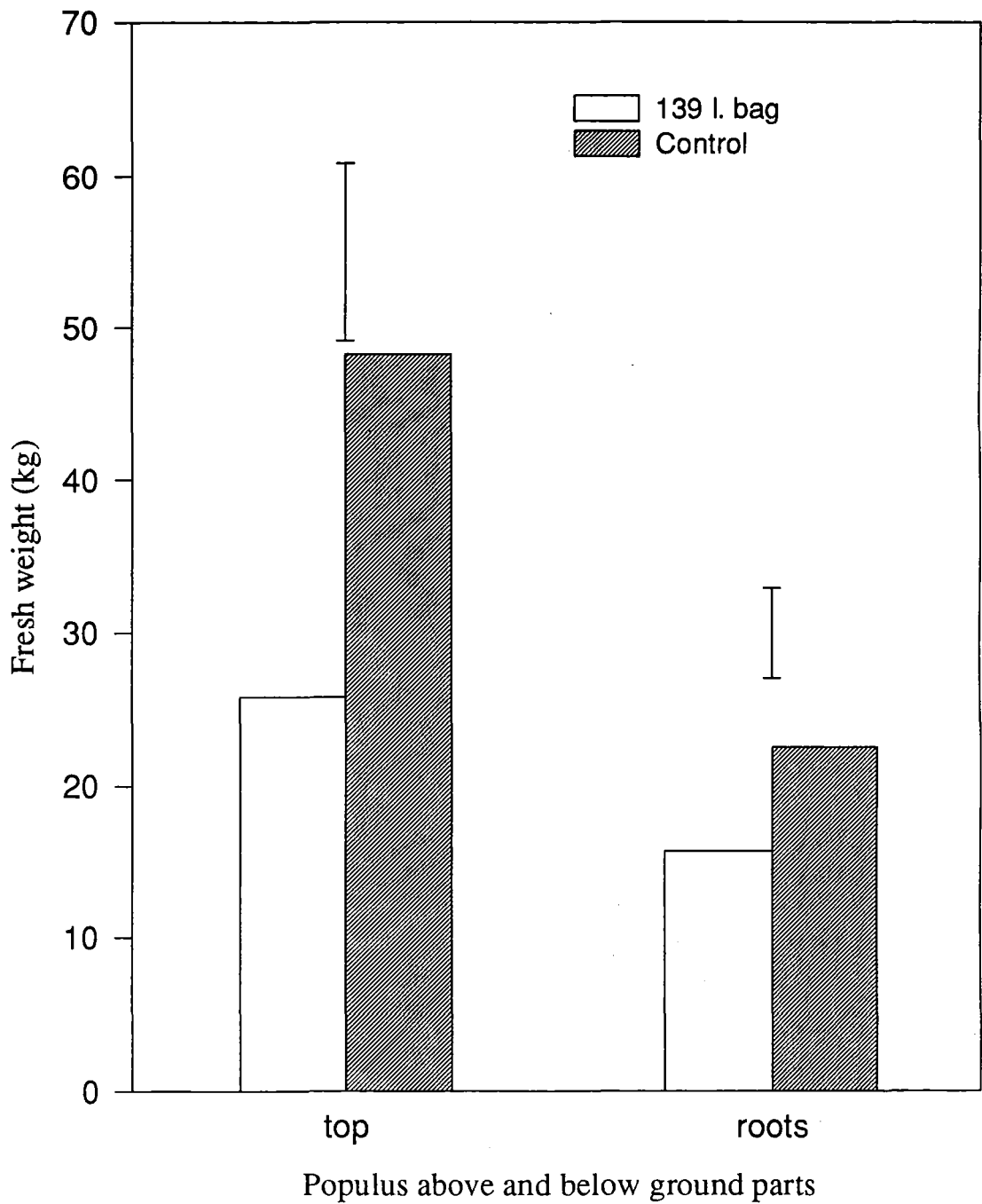


Figure 4.4.3. The effect of 139 litre bag and 139 litre no bag treatments on the fresh weight of *Populus*.

Roots Tr Anova $P = 0.027$

Top Tr Anova $P = 0.001$

LSD at 0.05 is represented by a capped vertical bar

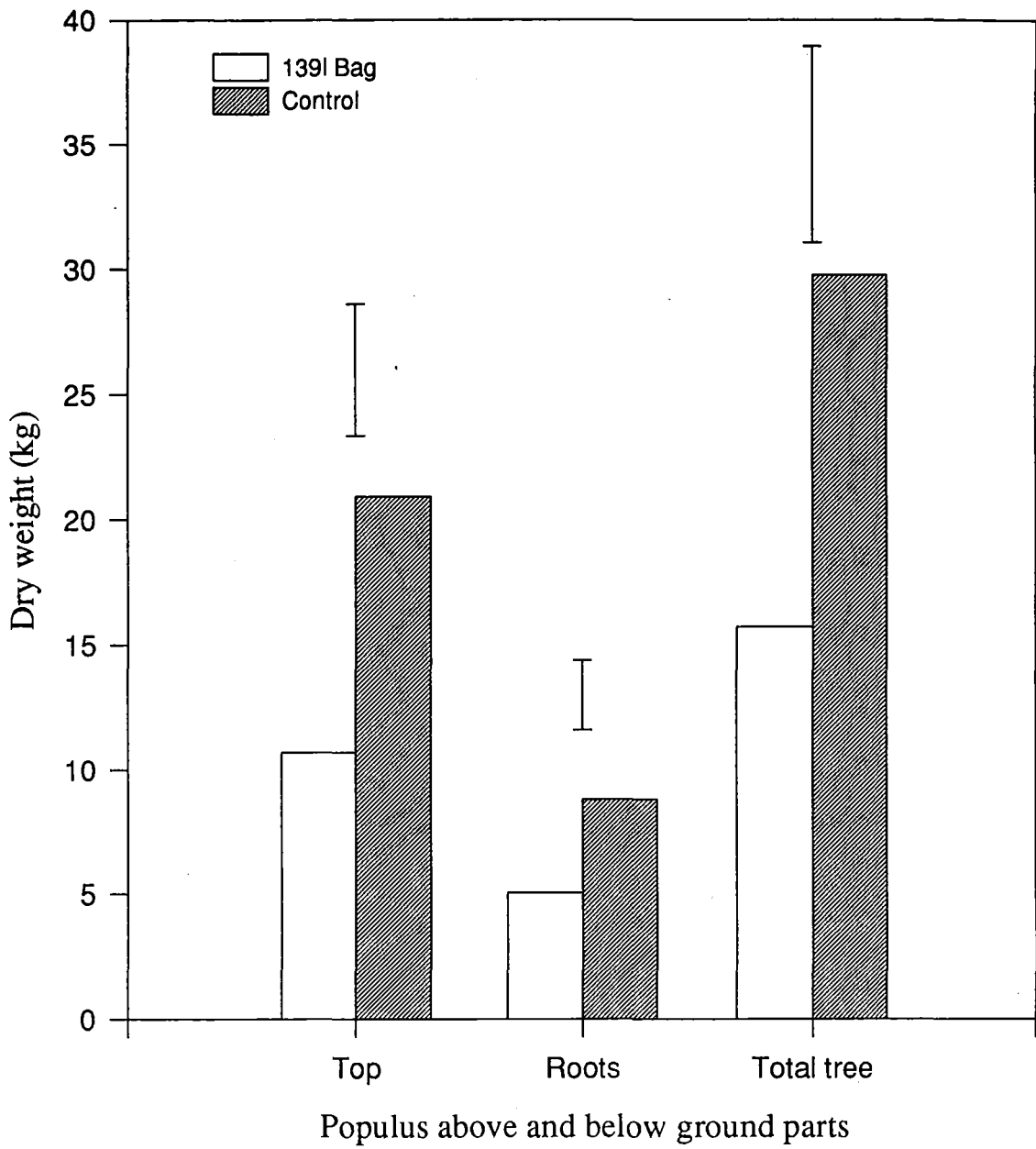


Figure 4.4.4. The effect of 139 litre bag and 139 litre no bag treatments on the dry weight of *Populus*.

Top Tr Anova $P = 0.001$

Roots Tr Anova $P = 0.012$

Total Tr Anova $P = 0.002$

LSD at 0.05 is represented by a capped vertical bar

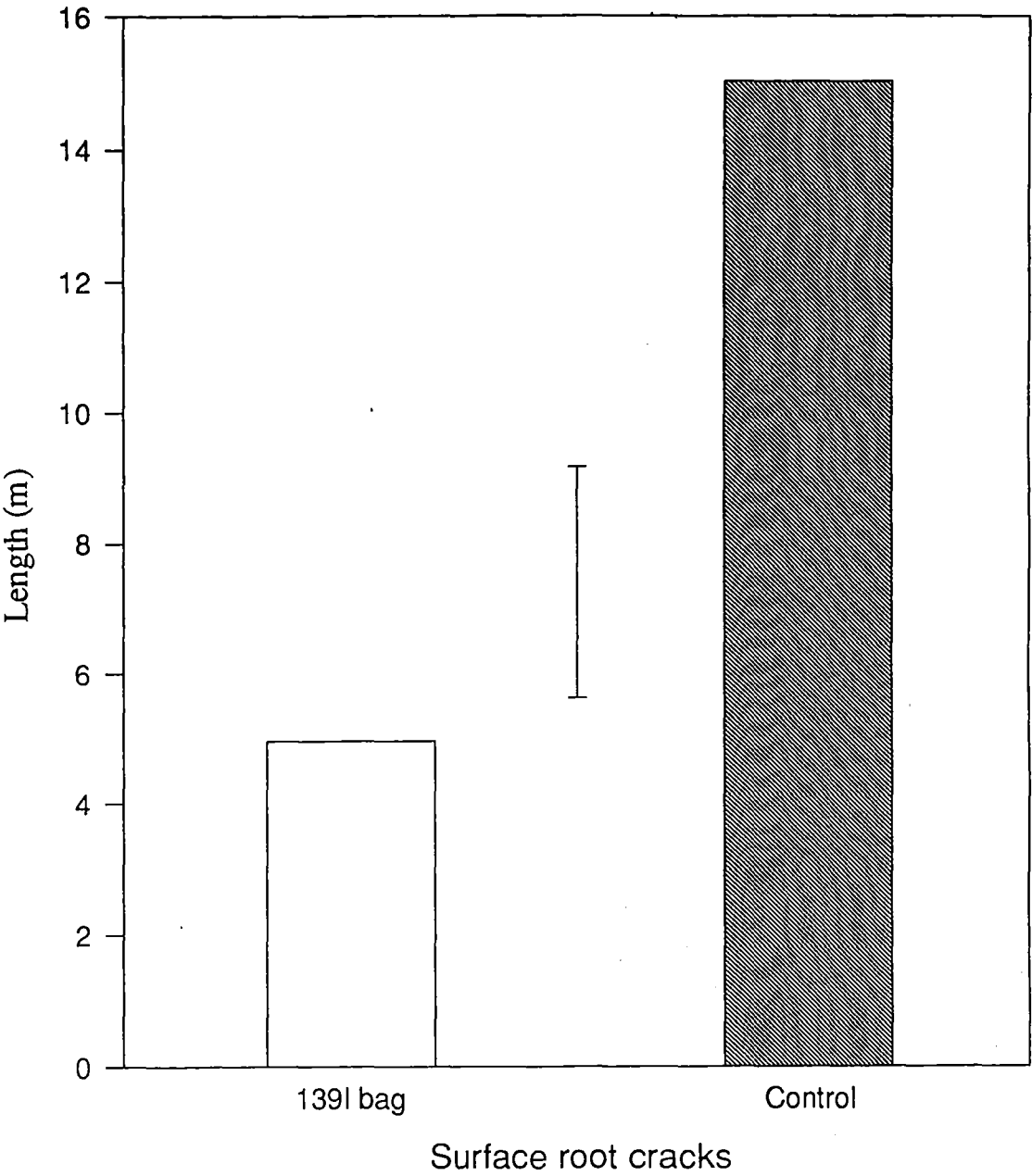


Figure 4.4.5. The effect of 139 litre bag and 139 litre no bag treatments on the mean length (m) of root surface cracks of *Populus* after three seasons growth.

Root crack length Tr Anova P = 0.001

LSD at 0.05 is represented by a capped vertical bar

4.5.0. Experiment two: Force required to topple *Dodonaea viscosa* 'Purpurea'

This experiment measured the amount of force required to topple *Dodonaea* trees, simulating the effect wind might have on trees with a large 'sail area' to root volume growing in bags. The three remaining replicates from each treatment were used at the end of two growing seasons, before the measurements reported in the previous results section were made. The results shown below are similar to earlier results for *Dodonaea* which showed greatest growth in the 24 l bags. The size of the trees in relation to bag size appeared to have made the trees more resistant to being toppled, relative to trees in other treatments. This can only be explained in terms of the time trees have had to grow in the bags, which may have been insufficient to provide meaningful results.

4.5.1. Media

The force required to topple trees growing in potting mix was significantly greater than for trees growing in field soil for trees in bags (Table 4.8.), and for 139 l bag versus 139 l no bag treatments (Table 4.9.).

Bag volume and 139 litre bag versus 139 litre no bag had no effect on the amount of force required to topple trees. There were no interactions between bags, no bags and media type.

4.5.2. *Dodonaea viscosa* 'Purpurea' leaf colour

There was no effect of leaf colour on force required to topple *Dodonaea*.

Table 4.8. The effect of media on force required (N) to topple *Dodonaea* in all bag sizes after two seasons growth

Bag volume (l)	Soil	Potting mix	Main effect volume
4	724.5	864.9	794.7
24	991.4	1432.2	1211.8
65	631.7	1315.8	973.8
139	676.2	1034.1	855.2
Main effect			
media	756 a	1161.8 b	
Bag volume	P = 0.208		
Media	P = 0.016	LSD at 0.05 = 105.6	
Media * Volume	P = 0.546		

Table 4.9. The effect of media on force required (N) to topple *Dodonaea* in 139 l no bag and 139 l bag after two seasons growth

Bag and no bag	Soil	Potting mix	Main effect bag and no bag
139 l bag	832.6	1075.9	954.2
139 l no bag	314.1	1084.7	699.4
Main effect			
media	573.4 a	1080.3 b	
Bag and no bag	P = 0.273		
Media	P = 0.047	LSD at 0.05 = 127.6	
Media * Volume	P = 0.259		

4.6.0. Experiment three: An assessment of water loss through the potential wicking effect of geotextile fabric.

The objective of this experiment was to determine whether or not geotextile fabric bags act as a wick, facilitating faster evaporation from the media adjacent to the bag when part of the bag is above ground, as recommended, compared with bags set with the top buried at the same height as the surface level of the media. Water loss was measured at seven day intervals.

4.6.1. Results

Water loss for every measurement date showed no difference between treatments, indicating there was no wicking effect of the bag. (Figure 4.6.1. and Plate 4.1.)

4.6.2. A further examination of a wick effect

A small demonstration trial was set up on March 14th 1995 to consider the hypothesis that geotextile fabric bags may act as a wick drawing water up through the bag away from the roots of the trees.

4.6.3. Results

After two and a half hours the water soaked strip showed the dye had climbed 85 mm up the strip, while the dry strip showed minor movement along the edge of strip only to 11 mm from the base, with only the few millimetres that was sitting in the solution completely covered in dye. After the two and a half hours no further movement of dye up the geotextile fabric took place. (Plate 4.2.)

Water loss was shown to be quite variable even for replicates within treatments in experiment three. This may have been due to changes in air movement across the surface of each bucket, which may in part be affected by the height of the bag above the surface. Other influences on water loss may include the different places within the glasshouse, possible influences being the

amount of sun or shade as well as the draught through the glasshouse ventilation system. Variability can in part be explained by this as within each block of treatments the position the bucket was returned to in the glasshouse, after weighing, was changed in a controlled manner. Water loss as expected showed more than half of the water added (2000 ml), was lost within the first 21 days, while the second 2000 ml had still not been lost after a further 56 days.

Treatment results in experiment three showed small, non significant differences. Bags planted as per instructions with the top 50 mm of the bag sitting proud above the ground level do not act as wicks demonstrating that geotextile fabric bags have no affect on water loss, therefore can not be expected to affect the root restriction process by drying out roots in bag zone. The results of this experiment were confirmed by a second minor experiment where a water soaked piece of geotextile bag fabric and a dry sample were had one end placed in dye. The results from this clearly indicated that liquid was only able to move up the fabric by capillary action while it was wet, as soon as the fabric dries no further movement of water occurs. In the field situation during dry weather and non irrigation periods the fabric would quickly dry above ground level and would not draw water up through the fabric. Gravity clearly has an effect on the water movement and drying rate at the top of the strip as well. It is assumed however that below ground level the bag in moist soil would remain moist also while intimately associated with the surrounding soil.

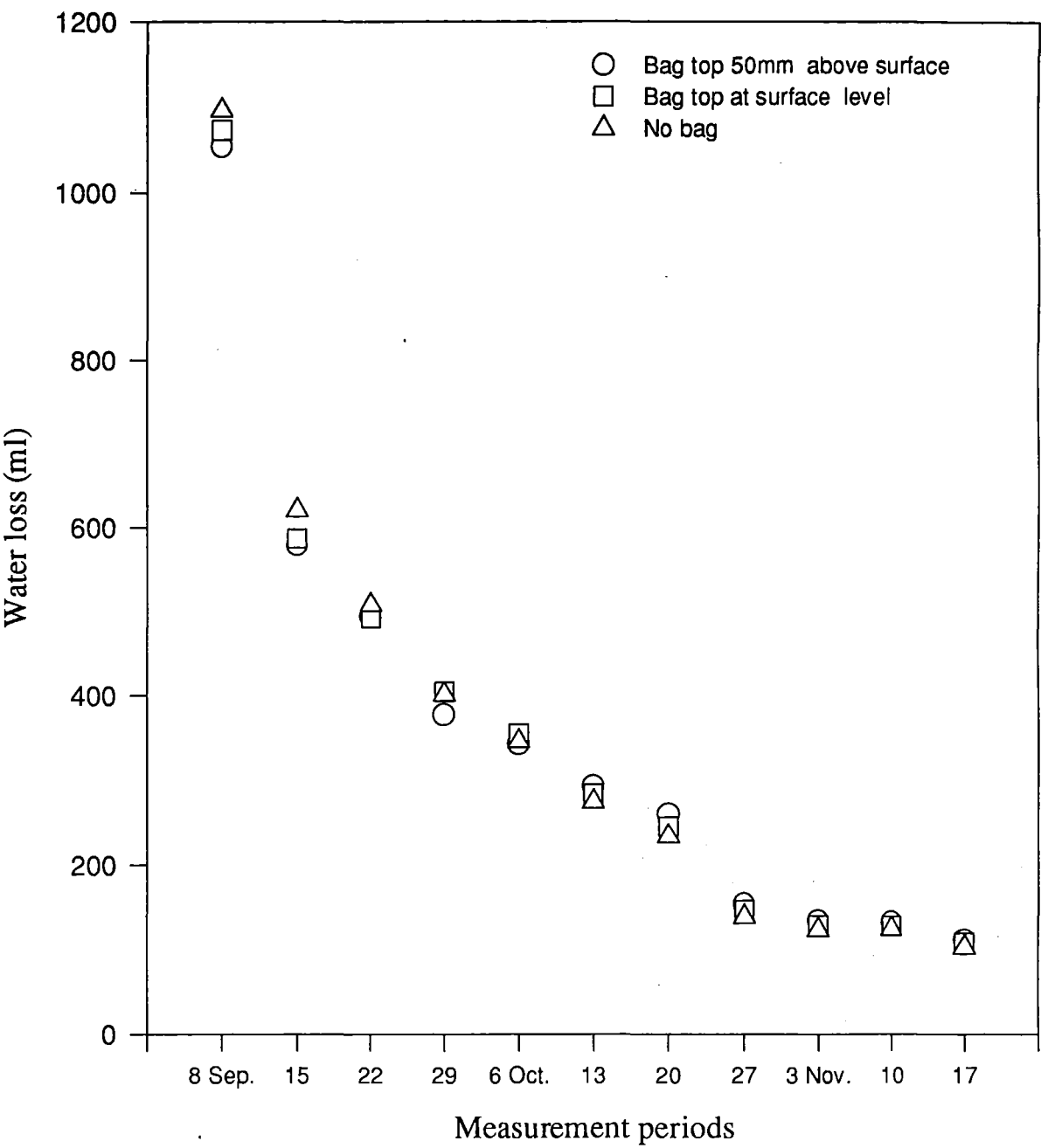


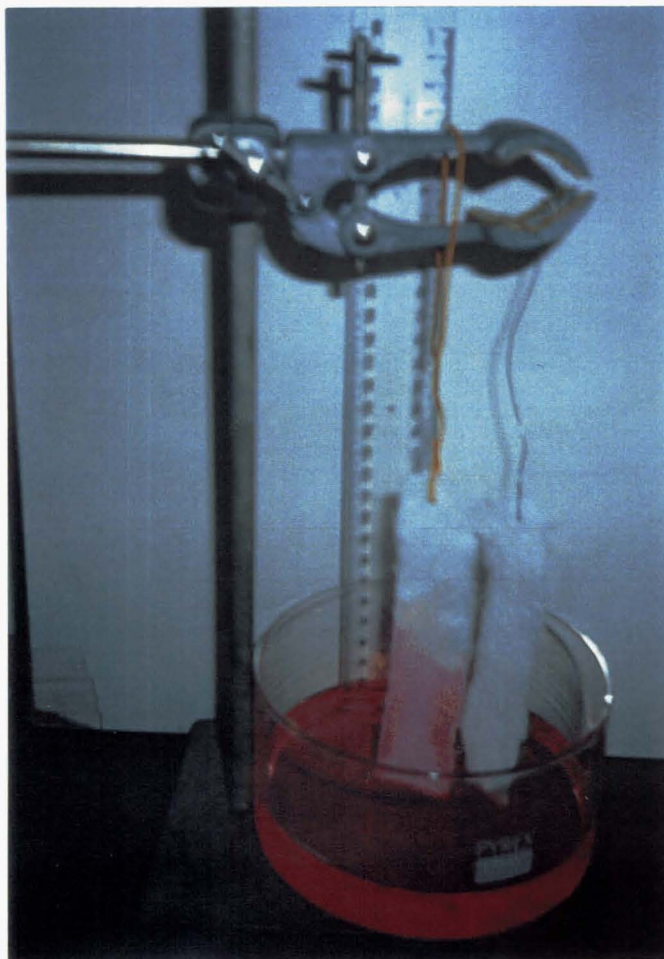
Figure 4.6.1 The effect of bag top relative to surface level of the medium in relation to water loss.

Water loss Tr Anova n.s. for each measurement period.

Plate 4.1. **Measuring water loss to assess the wicking effect**



Plate 4.2. **Capillary movement of water on wet and dry geotextile fabric strips**



4.7.0. Experiment four: An assessment of the number and size of holes in geotextile fabric before and after applying lateral tension.

The objective of this study was to accurately assess the number and size of the pre punched holes in the geotextile fabric and to determine what the effect, if any, lateral tension applied to the fabric would have.

4.7.1. Results

Sanderson pers comm. (1996) provided the following information on the sample of geotextile fabric provided from the same batch of bags as used in the field trial. The fabric is non - woven, felted and needle punched. Tests carried out on the fabric using a projection microscope showed hole diameter varying in size from 200-500 μm (0.2-0.5 mm) with an average of 400 μm . There were no perfectly "clear" holes, although many were crossed by only a few fibres. The number of holes varied (5 samples) between 40 and 54 holes per cm^2 , with a mean of 48 holes / cm^2 . (standard deviation of 5.52).

4.7.2. Fabric after extension

The stretched samples were examined under the projection microscope. It was apparent that the number of "nearly clear" holes had diminished, as most were obstructed with a thicker mass of fibres. In the sample stretched parallel to the needle punch lines it was difficult to identify many obvious holes at all. The holes that remained were smaller, about 200 to 300 μm , as well as being less well defined. See plates 4.3-4.6.

The number of holes per cm^2 after stretching were counted on the projection microscope.

Sample 1	(parallel)	15 holes / cm^2
Sample 2	(45 ⁰)	36 holes / cm^2
Sample 3	(90 ⁰)	36 holes / cm^2

The fabric did not appear to lose significant thickness with extension.

Plate 4.3. Geotextile fabric showing needle punched holes - no lateral tension applied.
(Square represents 1 cm² (mag. 50x)).

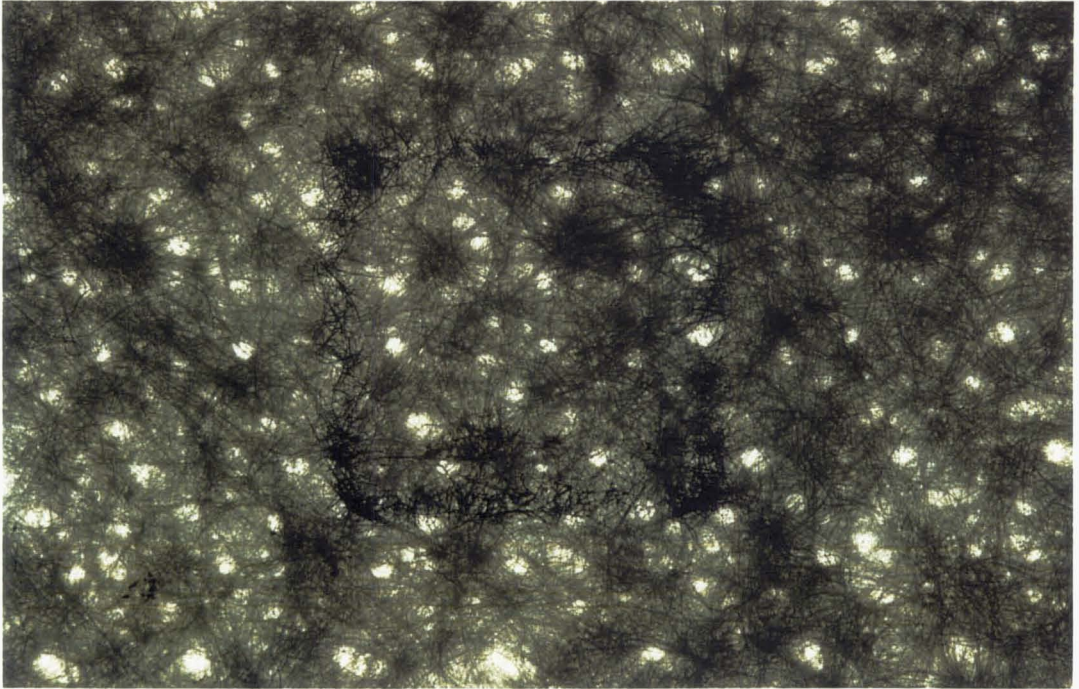


Plate 4.4. Lateral tension 20 newtons applied in direction at right angles to lines of holes
(mag. 50x)

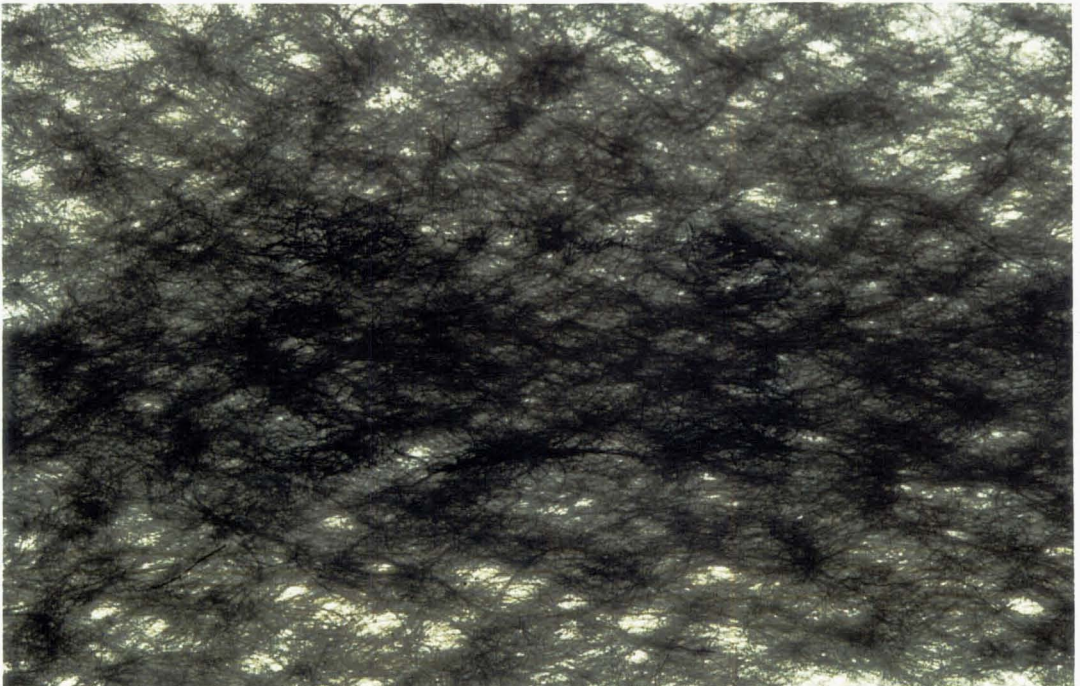


Plate 4.5. Geotextile fabric hole - no tension (each unit shown in scale is 20 microns (mag. 200x)

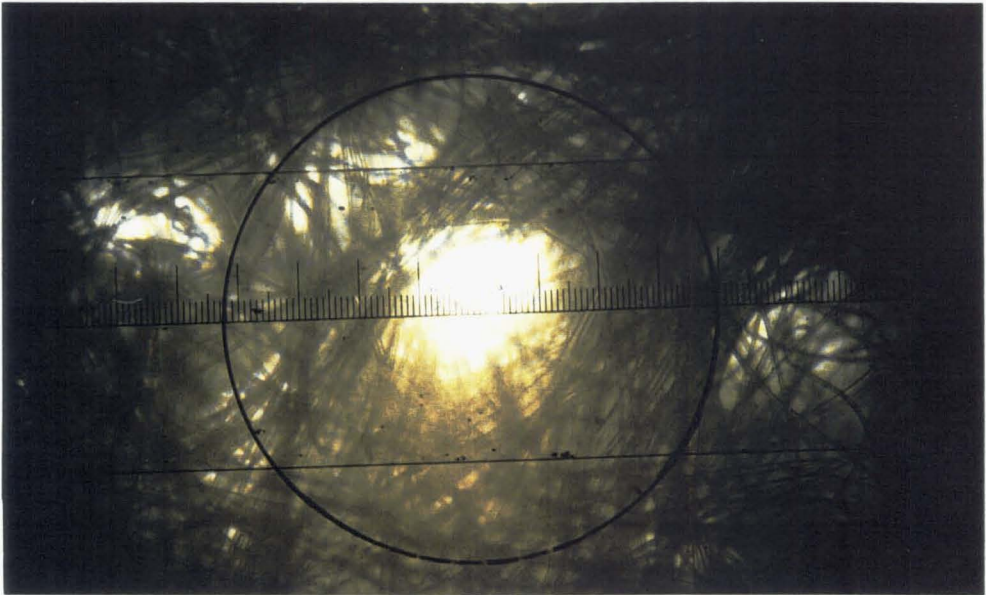
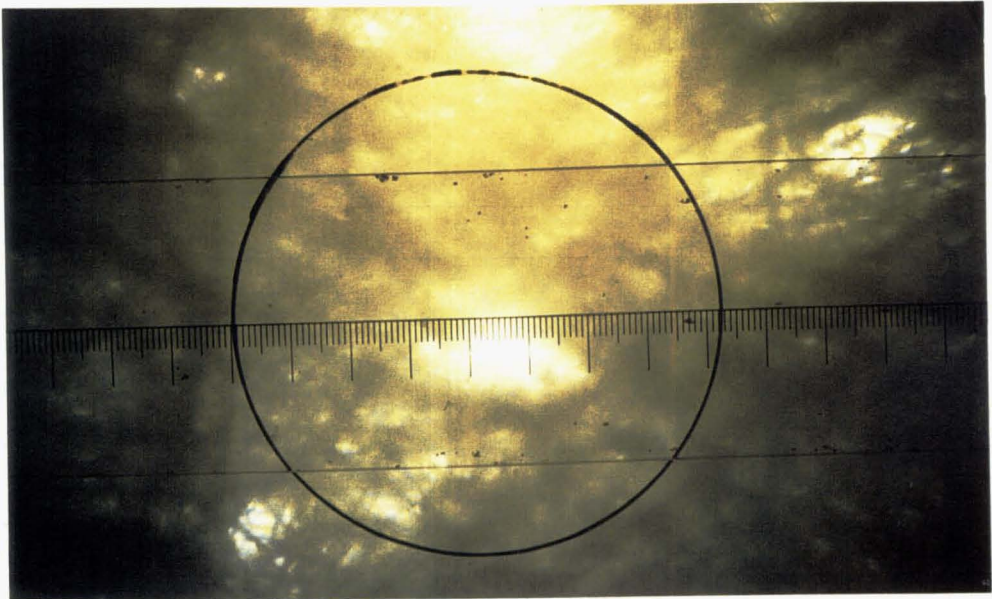


Plate 4.6. Geotextile fabric hole - tension applied (each unit shown in scale is 20 microns) mag 200x



4.7.3. Geotextile fabric root constriction process

Observation showed as the root on the inside of the geotextile bag enters the fabric it does not always take the shortest route directly out through the bag wall. In many cases the root was observed growing within the fabric for a considerable distance before exiting the bag. For the roots that were seen to exit directly through the fabric more or less at a right angle to the fabric the process of constriction appears to follow these steps.

- a. For the roots exiting directly through the bag, in all cases that were measured, the root diameter was less than the 3 mm at the point in the wall fabric where the root is constricted as implied by use of the standard probe test using a 3mm needle in Root Control Systems (1993). See plate 4.8.
- b. After the root exits the bag there is an increase in diameter of the size of the root adjacent to the point of constriction within the fabric on both sides of the bag wall.
- c. On the inside of the bag the roots could take two forms, either a swollen node developed at the end of a more or less "normal" sized root, or the root became thickened for all of its length "finger like" in appearance. During this process a number of lateral roots have also formed and these appear close to the fabric within the confines of the bag and follow the direction of the bag surface itself or are at right angles to the main root. See plate 4.7.
- d. The roots immediately adjacent to the outside of the bag fabric (and constricted root area) are swollen, but taper off as they extend further away from the outside of the bag surface.
- e. The last stage is seen with the epidermis of the roots outside changing to a dark brown indicating senescence and in some observed cases death for that portion of the root. Internal root pressure within the bag as root volume increases, and wind catching the canopy of the tree above ground creating a fulcrum effect on the restricted root volume in the bag region, may influence the dead root finally shearing from the outside of the bag wall.

Plate 4.7. *Populus* ‘Tasman’ root travelling circumferentially within fabric (The same effect was seen with *Dodonaea viscosa* ‘Purpurea’)



Plate 4.8. *Populus* ‘Tasman’ root restriction showing large bulbous root mass that builds at bag interface. Note the restricted portion of the root at the centre of the bulbous area



Plate 4.9. Restricted *Populus* ‘Tasman’ root at bag interface showing adventitious shoot development from the portion of swollen root

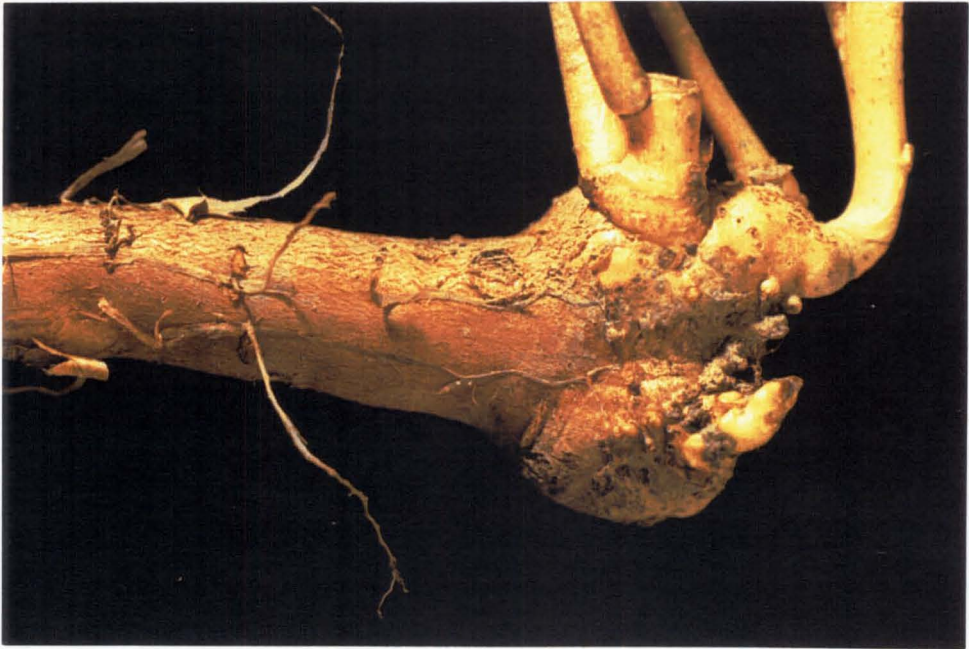


Plate 4.10. Restricted *Populus* ‘Tasman’ roots, all bag sizes from left 139 l to right 4 l. Washed roots after three seasons growth, alternate from left to right -potting mix, and soil for each bag size.



CHAPTER 5

DISCUSSION

5.1. Summary

In the first experiment an attempt was made to determine if bag volume and media were likely to have an effect on the longer term growth of two tree species. Early results showed that media had an effect on the speed of growth and this effect was maintained for trees over the life of the experiment. However the effect of media reduced in the second and subsequent years for both species. Bag volume had no obvious effect on tree growth for either species for the first seasons growth, but for *Populus* 'Tasman' had an effect over time. The smallest bag sizes had a strong effect in restricting growth by the end of the third season. Although the two species were harvested after different periods of time, there were strong indications that the effect of media and of bag volumes used in this experiment were similar.

In experiment two results showed that the amount of force required to simulate wind throw of trees was, at the time of measurement, closely correlated with the different media. In many instances trees grown in bags compared with trees not in bags were harder to pull over. Bag volume did not have any effect. This experiment must, however be, seen in the context of the growth stage related to the age of the trees being grown and the bag volume available. It is most likely that as trees grew in size that the relationship between roots and top would change as would factors such as stability both within and outside of the bag as the ratio of larger diameter roots to smaller diameter roots also changed. If the experiment were to be repeated bag volume may well become a significant factor with older trees as roots inevitably occupy a greater volume of space within the bag as secondary thickening increases.

In experiment three geotextile fabric bags were shown to act as wicks only while the bags were wet and water was able to move through capillary action. As soon as bag fabric dried out no further water loss occurred. This experiment suggests bags do not restrict root growth by way of the fabric drying out through a wicking effect. Water loss was not affected

by the presence of bag fabric above the surface of the medium, at surface level or where there was no bag.

The fourth experiment showed lateral force applied to geotextile fabric reduced the number and size of needle punched holes, although it did not appear to alter the thickness of the fabric significantly with an applied force of 20 Newtons.

5.2. Growth response

The root : shoot ratios for *Populus* after three seasons growth showed that the roots with the most severe confinement (4 litre bags) had the lowest root : shoot ratios with significant linear regression (second order). *Dodonaea* after two seasons growth showed a similar trend. Trought and Drew (1981) showed that the allocation of dry weight by plants between the root and shoot is influenced differentially by the type of environmental stress to which the plant is exposed. Chung (1983) showed with cucumber the influence of the stem in altering the relationship between dry matter partitioning within the plant. Chung (1983) states "the presence of a stem can be a significant factor in its (cucumber plants) adaptation to environmental stress". Al Sahaf (1984) working with tomatoes and Chung (1983) with cucumbers found mineral uptake was enhanced when roots were confined when considered in relation to unit root length.

Walmsley (1989) found no difference when 576 two year old nursery transplants of *Fraxinus excelsior* were fertilised with 12 different combinations of NPK. Although not significant there were trends that were apparent, nitrogen in all NPK treatments enhanced total weight, shoot and root weights and led to an increase in root : shoot ratio with the exception of NP treatments where shoot and root growth was reduced. In experiment one the root : shoot ratios were clearly greater for both species at the time of harvesting where the trees were grown in potting mix, rather than field soil. The trees in potting mix in the first year had additional N, relative to those trees in field soil. The N in the potting mix cannot be discounted as a factor influencing the higher root : shoot ratio observed for both tree species at the time of harvesting. It was assumed, however, that this effect would be reflected primarily in the first seasons growth. The root ; shoot ratio was not, however, assessed until the trees were harvested, either one or two seasons later, depending upon the species. From the results

in experiment one, it is clear that the initial effects of the additional N can be carried over for at least one to two seasons. Coutts and Philipson (1980) showed a reduction in the root : shoot ratio is commonly associated with an increase in fertility. This could suggest that the N levels in the potting mix in experiment one may be less important than the texture and bulk density of the different media.

5.3. Media

The two types of medium used in this study had significantly different physical and nutritional characteristics. The potting mix described in Table 3.1.1. indicates a medium with particles mainly in the larger range of sizes compared to the silt loam. The potting mix also has larger pore space compared to the soil. Harris (1992a) states “water and air movement and ease of root growth through soil are determined by pore size, not necessarily by the size of soil particles”. Harris (1992a) also suggests particles in the soil are not discrete units, but are grouped in aggregates or granules, each of which acts as a large particle as far as water and air movement are concerned. Soil structure indicates the degree to which particles may be aggregated and soil structure may easily be destroyed by compaction or through chemical dispersion (eg., in high sodium soils). Goh (1987) states for nutrient uptake to occur energy is needed and this is obtained from root respiration. For root respiration to occur, oxygen is essential. The medium plants grow in must contain sufficient air. Harris (1992a) points out that loose well aggregated soil will compact more than a soil that is less well aggregated. Soils with a range of particle sizes can be more severely compacted than soils of a uniform texture regardless of particle size because small particles fill the pore spaces between larger particles.

Bulk density can be a useful measure of the porosity of soil, particularly where mineral soil particles are of a similar density. Bulk density is a measure of the weight of a given volume of soil (and other media) and is usually expressed in g/cm³. A knowledge of the texture of the soil may also be important, however, especially when some soils may have the same bulk density, but particle sizes vary. Smaller particle sizes may restrict movement of air and water to a greater degree than larger pores. In experiment one growth was typically greater in trees growing in potting mix in year one and the cumulative effect of that faster growth was carried over, even though in year two and beyond there was no difference between

media in terms of annual incremental growth. The faster initial growth of all parts of the tree including the roots meant that the occupation of space within the given volume of media occurred sooner. The effect of this in the smaller bags was that compaction of the media occurred soonest and the consequent effects of compaction - reduction of pore size, air space, ability to absorb water and nutrients come into play in reducing the ability of the tree to grow.

5.4. Observations on the effect of root growth and geotextile fabric bags on media compaction (Table 4.5.)

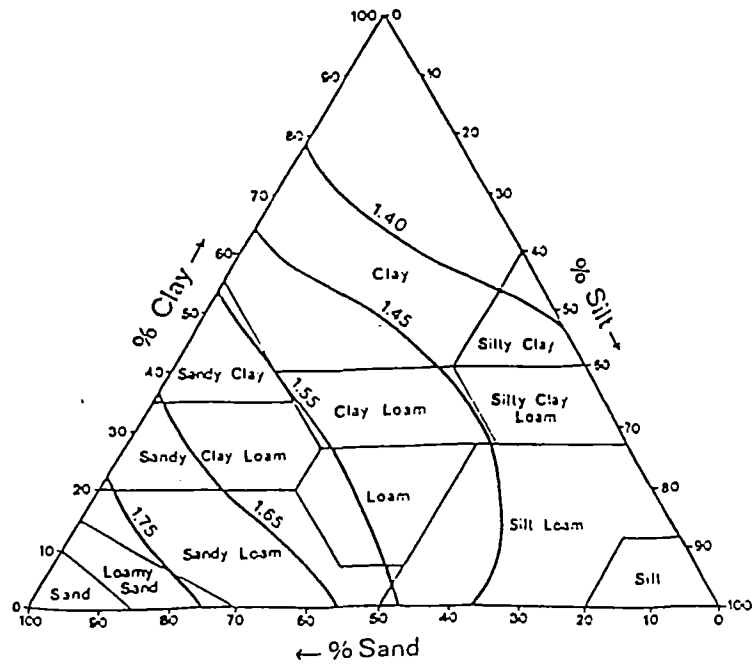
- 1. The greatest level of compaction occurred in 4 litre bags, there was no difference between levels in the other bag volumes at the point of harvest.
- 2. The quantity of roots within the bag is not static and changes with time.
- 3. As the volume of the roots increased there was a corresponding increase in the levels of compaction of the medium. This is exacerbated by the geotextile bag in that the tree is able to exploit space within and out of the bag in a more or less unrestricted manner in the initial period of growth by roots growing out through the bag. This space as a ratio based on tree size over time rapidly becomes unavailable to the plant especially in the smallest bags as the medium within the bag is increasingly compacted. The root : shoot ratio in the smallest bag size favours shoot growth.
- 4. As the medium became more compacted there was a corresponding increase in bulk density. This is associated in a general sense with a reduction in both particle size and pore space within the growing medium. Pore space at any given time is occupied by either air or water in fluctuating proportions. Pore space can be calculated from the formula:

Bulk Density
% pore space = 100 - ----- x 100
Particle Density

Donahue et al. (1971)

- 5. The degree in which this change occurs is fastest in the smallest bags.
Morris and Lowery (1988) superimposed bulk densities on the USDA soil triangle (Figure 5.1.) as an indicator of where root growth and function are likely to become restricted.

Figure 5.1. Soil triangle with bulk densities superimposed



Morris and Lowery (1988) suggested that compacted loam would have a bulk density of 1.45. The mean bulk density of the media used in this study show extreme levels of compaction for the smallest bag volumes. Bulk density for compacted soils vary depending on a number of factors, however the bulk density levels calculated suggest the trees in this study may well have reached the point where trees in smaller bags would no longer continue to grow. The bag sizes indicate compaction is the least severe in the largest bag sizes. What is not certain is the effect of roots remaining outside the bag wall. With the two complete replicates of *Dodonaea* that were measured a greater proportion of roots in bags with potting mix were inside the bag compared with soil (figure 4.1.8.). This suggests that initial root expansion and internal pressure occurred more quickly in the potting mix. The reasons this occurred was presumably because of the level of N and the lower bulk density of the medium to begin with. It was also seen with *Populus* after three years growth that the distribution of root diameters > 5 mm (Figure 4.1.6.), were significantly greater than root diameters of < 5 mm in potting mix. With *Populus*, it was also obvious from the dry weights (Figure 4.3.5.), that roots cut fresh < 5 mm diameter were not greatly different over all bag volumes, whereas in the larger volumes the dry weight of roots > 5 mm diameter when cut fresh increased at a much greater rate. This leads to the conclusion that while the bag volume effect is significant, secondary thickening ultimately causes tree growth to slow through increasing bulk

density. This also needs to be considered in light of the changes in the nature of the holes in the geotextile fabric.

5.4.1. Potential for media loss from the bags

There is a possibility that some media loss may have occurred from geotextile fabric bags, although there was no obvious signs to suggest this did occur and no measurements were attempted to quantify that during this experiment. Any media that is lost would have an effect of reducing the potential increase in bulk density caused by root expansion within the bag.

5.4.2. Possible ways media could be lost during the growing period.

- a. Soil particles being finer and more soluble and may move through the fabric wall when squeezed under pressure with increasing root volume. It was observed when washing tree roots bagged in soil, the water was dirty coloured, indicating the presence of fine soil particles, continuously washing through the bag walls. This was not as obvious with potting mix.
- b. Media could be lost from bags by upward pressure with soil or potting mix being lost from the bag at the open surface area. While this was not obvious if it were occurring, it can not be discounted.

5.5. Influence of the geotextile fabric in root restriction

The needle punched holes in geotextile fabric bags changed in number and diameter when lateral force was applied to the fabric. With lateral force the number of holes reduced and the size of the individual holes reduced also. Holes became occluded with matted fibres which would make root penetration of the holes more difficult as the fabric was tensioned. It is anticipated that this tension would occur over time as roots expanded within the given media of any bag and as a consequence would presumably make root penetration of the fabric more difficult. Henry (1993) showed the roots of grapes were unable to penetrate pore sizes of less than 200 μm . The holes affected by stretching the fabric laterally reduced from being between 200-500 μm to being around 200-300 μm , greater lateral force may have reduced the hole size further. The number of holes was also shown to diminish significantly with lateral force. With the sample stretched parallel to the needle punched holes it was difficult to identify many obvious holes at all. All of the bags checked for this study showed that the lines in the fabric

were made in a circumferential direction around the bag wall. It was not possible to give a measure of the amount of tension the fabric was placed under in the field experiment, with the exception of the smallest bag size there was no obvious stretching of the fabric indicating any volume change. In the smallest bag size, the base of the bags was stretched outward in a convex manner, indicating there may be a very small volume change only. The fabric was, however, extremely tightly bound to the roots and media which it was largely containing. The degree to which fabric could be stretched was not measured, but appeared to be very little.

The conclusion reached in relation to the bag fabric was that over time as root volume expands, the bag soon begins to act as a container, preventing root growth from penetrating the wall of the fabric, as it had been able to do at the beginning of the study when roots were able to grow through the needle - punched holes.

5.5.1. Bag volume : bag fabric surface area

A comparison of the surface area of the geotextile fabric bags with the bag volume shows the smallest bag volume has a very large ratio of surface fabric area compared with the other bag sizes. The 4 litre bag in relation to the other sizes has nearly two times the ratio as 24 litre bag, three times the 65 litre bag and four times the ratio of the largest 139 litre bag. The 24 litre bag in relation to the 65 litre bag has 43% more bag fabric surface area and is almost twice the fabric surface area in relation to volume as the 139 litre bag. The 65 litre has approximately 29% more surface area than the 139 litre bag. (Appendix 4.)

Understanding the ratio of bag fabric surface area to volume is useful in determining the effect of the restriction process itself, in association with the changes to the fabric under tension. The bags with the largest surface fabric ratio to volume become pressured earlier from internal secondary root thickening than the larger bags, based on the relative similarity between the total amounts of growth young trees of the same age are going to be able to make initially. Associated with this early pressure is the faster compaction of the media which is contained by the larger ratio of fabric to volume. It is the combination of these factors associated with the continual requirement for the tree to increase both root diameter and root length throughout its life that lead to early restriction occurring.

5.6. Speculation on how the root mass inside the bag assists restriction

Within any particular bag size the volume is more or less fixed (excepting that some limited stretching occurs as shown by pressure testing of the fabric and in this study, only in the small bags was a stretching of the bag and a small increase in volume obvious). During tree growth there is an increasing internal pressure on the surface of the bag wall as the roots within expand. This increase in pressure could occur locally at the point of constriction or could be exerting pressure on the whole bag surface after a period of time. The additional pressure on the root, through the increased tension of the fabric may be important to the final restriction process. Associated with the fabric being increasingly put under tension and the needle punched holes reducing in size, there is the pressure of roots penetrating the fabric to develop secondary thickening. The restriction of the root penetrating the bag at right angles inevitably occurs. Internal root growth may also exert a shearing pressure based on some limited movement at the constricted point as that internal root bulk grows.

5.6.1. Direction of root growth within bag

The direction of root growth within the bags was markedly different with potting mix and soil. The roots in bags with soil tended to radiate outward from the centre of the bag as would be expected of a well formed root system. Henry (1993) showed roots tend to be longer and less branched where the pore diameter of the medium is larger. This did not appear to be the case in this study as roots within the potting mix were much more branched. Chung (1983) showed that the roots of cucumbers grown in low N. produced roots that were thicker in diameter and longer than those in high N. solutions which were shorter and more branched. It would appear that the effect of the bag wall and the N. levels in the potting mix in this study overrode differences in the pore diameter of the media. In the smaller bags roots in both soil and potting mix had become grossly deformed in both species. In potting mix roots showed they were more likely to grow in any direction, growing in the direction of least resistance. In many instances roots having reached the bag wall, then changed their orientation with new growth along the bag wall and sometimes directly back toward the trunk. Other roots in smaller bags were seen to have redirected growth upward or downward at the bag wall. (Appendix 5, Plate 1.).

5.7. Occurrence of root escapes in *Populus* 'Tasman'

Root escapes were clearly evident after three years growth of *Populus* 'Tasman', although it was not clear from the results of this experiment when the actual escapes from the bags first occurred. Relative growth rates were analysed for all measurements prior to harvesting, but the measurement periods were not frequent enough to show significant differences in growth.

5.7.1. Possible reasons for root escapes

The different media had a significant effect on the number of root escapes produced. Potting mix produced trees where roots escaped from the bags almost four times more than root escapes from trees in field soil.

a. Potting mix

Faster growth rate of roots and shoots occurred in potting mix, relative to those in soil. Roots were able to exploit greater depth as pore size in potting mix is presumably not compacted as quickly as in soil (which starts off with a smaller pore size). Although not measurable it is probable that oxygen levels are higher within the potting mix. There was a trend showing the greatest numbers of root escapes occurred in large bags in potting mix compared with the smaller bags. This may be related to greater compaction of media within the smaller bags. The compaction would occur at an earlier stage based on the smaller volume of media that can be exploited, the more rapid reduction in pore space of the medium and the reduction in the diameter of the punched needle holes in the bag fabric as this also more quickly comes under tension in the smaller bags.

The larger number of root escapes and the greater size of the trees in the larger bags is related to the greater volume of media and the greater surface area of fabric that can be exploited. The greater surface area of the fabric would allow a larger number of roots to become constricted with more secondary laterals able to enter the fabric and travel within the

fabric in a circumferential direction. In smaller bags the restriction process is unlikely to occur until near the end of the first seasons growth, by this time however secondary thickening may have already had an impact on increasing soil bulk density and the increased tension on the fabric container. The smaller bagged trees may become restricted earlier through insufficient reserves, where the root:shoot ratio favours the shoot earlier, based on the inability of the roots to penetrate the more rapidly compacting media and the holes closing earlier in the bag fabric walls. The roots of trees in smaller bags may start to live on the carbohydrate within the system at an early stage whilst influencing changes in leaves which may need to reduce stomata opening, which in turn influences ethylene production, leaf size and number reduce and ultimately photosynthetic capability is lowered.

b. Soil

Trees growing in the soil grew more slowly than those in the potting mix. These trees also were growing in a medium with a measurably higher bulk density that is less porous than the potting mix to begin with. Over time with an increase in root diameter the tree increases the compaction of the soil and reduces the number and diameter of holes in the geotextile fabric which ultimately leads to a lessening of vigour for the tree. In soil the whole process has been slower than in potting mix and the slowness of growth itself may help the restriction process occur over a longer time period. As the soil becomes more compacted and the bulk density increases this may slow growth sufficiently, such that roots may be unable to grow through the bag as has occurred in the potting mix. The initial nitrogen added within the potting mix may be also responsible in part for the faster growth of the trees in potting mix initially.

5.7.2. The way roots exit geotextile fabric

Roots were observed both in *Dodonaea* and in *Populus* 'Tasman' growing within the geotextile fabric in the bag wall circumference. See plate 4.7. It was observed that roots did not always enter and exit the fabric of the bag in a radial direction from the trunk. While no major root escapes were observed in the *Dodonaea* to the point when they were finally harvested (late 1995), the *Populus* 'Tasman' did produce major root escapes that were observed by early 1996. Suckering outside some of the bags containing *Populus* 'Tasman' was seen earlier than this. The root escapes have occurred by orientating the direction of the root

out of the bag by travelling within the fabric of the bag for varying distances before finally exiting the bag. This simply allowed the root to thicken radially over time (and with a certain length of root) and then burst through the bag after having weakened the fabric for a distance along the wall. Roots which simply exited the bag fabric in a radial direction out from the trunk appear to have been successfully restricted in both tree species. It is this restriction, however, and the subsequent production of new lateral roots reorientated along the bag wall which creates the potential for roots to escape. Indication of this potential were observed in both species. (Appendix 5, Plate 2,3,4 and 5.)

5.7.3. Means of root escape from geotextile bags

- a. Roots travel within the bag fabric for sufficient distance to be able to grow in length, at this point the root is able to force out the bag as secondary thickening occurs. The root is within the third dimension (thinnest part) of the fabric with the least physical resistance.
- b. The faster the initial growth of the tree, the more likely a tree will have greater carbohydrate reserves available to go into secondary thickening of both trunk and roots, both of which are exerting considerable pressure laterally on the bag.
- c. The lower resistance of the medium the more likely roots are to reorientate themselves and grow in new directions, in soils with a higher bulk density to begin with roots appeared less likely to branch.

The above factors clearly interact with each other influencing tree growth and the apparent success observed with fruiting tree and vines grown in bags may be partly explained by considering the sink fruiting trees provide as a means of absorbing and shedding excess carbohydrate. (Al Sahaf, 1984, White, 1995). In that way carbohydrate stored by the tree in the roots within a restricted volume could be minimised. Commercial fruit trees, for example, are usually selected cultivars, grown for high fruit yields, they are propagated vegetatively by budding or grafting onto rootstocks, which may also lead to smaller trees and higher yields. These trees because they are vegetatively propagated are likely to flower and fruit earlier than seedling grown trees and by doing so divert carbohydrate into fruit in the early years of

growth. Myers (1992) showed root confinement of peach and apple resulted in smaller canopy sizes than control trees, averaging 44% and 59% less respectively. He also found root restriction increased flower cluster number, fruit number, and percent fruit set on a per limb basis for apples. High fruit yields to canopy size would advantage trees grown in the bag system as root and trunk vigour would not occur as rapidly as carbohydrate is shed through the fruit. This process was not observed with the trees grown for this experiment. Growing trees in field soil would also be the norm. This fortuitously for the bagged fruit tree would also work in the favour of the bag, as a lesser proportion of roots are likely to occupy bag volume, based on what was found with *Dodonaea* grown in potting mix compared with field soil. A knowledge of how media in bags affects growth could be applied as a useful tool in the regulation of tree size : fruit ratio. Because flowering and fruiting was not part of this experiment, these comments are to a degree speculative.

5.8. The effect of bags and media on stability of trees in the field

5.8.1. Force to topple *Dodonaea viscosa* 'Purpurea' after 26 months growth

Trees grown in potting mix required more force to topple than those grown in field soil. Trees in potting mix generally grew faster, but because they have been shown to have a higher root to shoot ratio based on dry weight, are also likely to therefore have a greater number of smaller roots penetrating the walls of the bag. Considerable pressure needed to be exerted on these roots before they broke away from the inside of the bag. Control trees in potting mix were also more stable than control trees in soil alone.

The results obtained can only be regarded as valid for this species for the particular growing period, in this case 26 months. The relative force required to pull over trees in bags is likely to alter with time. It is conceivable that as a greater trunk diameter and a higher proportion of thicker roots fill the smaller bags that they become less stable. Conversely over time the larger bag, may become more stable as a greater proportion of roots grow through the walls of the bag. Changes in soil type and soil moisture conditions would also have an effect on stability. (Appendix 5, Plate 6).

5.8.2. Exception to the rule? - Wind throw of *Populus* 'Tasman'

After measuring the force required to pull *Dodonaea viscosa* 'Purpurea' over and showing bags provided greater stability in many instances than trees not in bags, it was surprising to find within a few months of removing the *Dodonaea* that some of the *Populus* in small bags blew over. With *Populus* 'Tasman' in the small bags that toppled, just one root escape had exited from the bag. This allowed that one large root to develop on just one side of the tree and ultimately it became a pivot point at which the tree could blow over. Tearing observed in the bag of one tree which blew over in the trial appears to have occurred during the fall. The root escape evident in the same bag, however, was clearly not caused by the tree blowing over as evidenced by the root diameter outside of the bag. (Appendix 5, Plate 7.)

5.8.3. Trees that blew over in 1996

The trees that blew over in early 1996 were more exposed to winds as the *Dodonaea* (which had been growing randomly in blocks amongst the *Populus*), had been fully harvested in the late winter / spring period of 1995. The three trees which blew over were all in 4 litre bags (150 mm diameter) and were growing in potting mix. Trees blown over occurred in blocks 1, 3 and 4. The other trees in block 5 showed clear evidence of root escape and suckering, whilst the tree in block 2 had been very slow growing initially and could not be regarded as typical of the growth in small bags for this trial. All other trees in the same sized bags in soil showed root cracks at the surface and on digging up these trees, there were indications that root escapes had occurred. The difference between the two media treatments appears to be based on the speed of growth between trees in the two media based on early differences in results. The fact that trees in potting media grew faster initially is presumably the reason why these trees blew over first, and it could be hypothesised that the other trees will blow over as the trees get larger, assuming only one major root escape occurred.

5.9. The wicking effect of geotextile fabric

Water loss by evaporation from the bag was shown only to occur from the part of the bag which sits above the level of the soil while the bag is wet after rainfall or irrigation. Water loss therefore from the bag is not an issue and does not compete with the roots for available water in the region of the bag itself. One would expect that as the surface soil dried out the in the field that there would be no water loss from the bag at all through evaporation.

CHAPTER 6

CONCLUSIONS

6.1. Media

Media was the most significant factor influencing tree growth in the first season for both species. In the second and third seasons the effect of media was no longer significant for height and trunk diameter. The cumulative effects of media showed that the larger growth in the first season was maintained so that media still had an effect by the end of the second and third seasons growth. Potting mix, with both a lower bulk density and higher fertility to begin with, produced larger trees than field soil. The same characteristics of potting mix, however, ultimately led to trees producing a greater number of root escapes in poplar than occurred in field soil.

6.2. Bag volume

Bag volume did not have any apparent effect on tree growth for most measurements until the end of the second seasons growth and even then the results were ambiguous. By the end of the third season, poplar was showing the limiting effects of bag volume on growth for most factors measured. In the smallest bags at the end of the third seasons growth, where there were no major root escapes, the bags were densely packed with the trunk base and thickened roots. At the media surface there was a very high density mat of short roots, all approximately 8-10 mm, pointing upward into space. The roots appeared to have no other available space to exploit within the bag and showed the root system was under extreme stress. This space appears to have been the only direction left for the roots to grow due to mechanical impediments within the bag through compaction and fabric tensioning.

The effect of bag volume occurred toward the end of the trial period, prior to that differences in growth were primarily related to media. The question this raises is, why did the effect of bag size take so long to manifest itself? It appears that only when the volume of the bag is increasingly filled with roots and compacted media that the limitation to growth occurs. If so, the

long term consequence for growing street trees in geotextile fabric bags will be problematic as trees progressively become under greater stress from declining root : shoot ratios.

6.3. Comparison of bag experience with the bonsai system

Part of the original hypothesis concerning the possibility of bags being able to restrict the growth of trees over the longer term was that geotextile fabric bags may act in a manner similar to the process of bonsai. The possibility was considered that if root turnover in the bag system occurred fast enough, then there would always be space for new root growth. Observations on the growth of tree roots in bags have shown this not to be the case for the species in this experiment.

The architecture of the root system develops differently to that of a bonsai plant in many ways (See Table 6.1.). The root system of a tree within a geotextile bag is such that providing the tree is correctly planted according to instructions the roots travel radially out until they reach the bag wall. At the bag wall the roots may grow through and are subsequently constricted. Inside the bag wall however, secondary laterals grow at right angles to the direction of the restricted root, these roots are now travelling in the direction of the wall of the bag. In the poplars some of the main roots branched at the wall and reoriented new root growth back toward the centre of the bag. In this way the tree roots grow where resistance is the least and fill the available space within the bag.

As the roots occupied more of the space within the bag, the media had also become increasingly compacted and was extremely difficult to remove from the roots in bags harvested. The extreme levels of compaction experienced in some bags leads to the conclusion that any new root growth within the bag itself would become progressively more difficult for the plant to produce.

There was no obvious evidence within the bagged root system of rotten or decayed roots indicating any turnover of major roots within the bag. It could be argued that high pressure washing of the roots may have removed evidence of this as the soil or potting mix was washed away. Reid et al. (1993) shows with kiwifruit (*Actinidia deliciosa*) that there is considerable turnover and loss of roots in any one year, with only 8% of roots formed living for more than 252

days. In this study, however, the roots and trunk base that developed secondary thickening were the critical factors, and root turnover, while it may have occurred, appeared of no significance to the final results. As a higher proportion of the root system of the tree is ultimately contained within the bag, this becomes one of the main reason why the tree is smaller than it would otherwise be. It also leads to the conclusion as to why growing trees long term in geotextile fabric bags must ultimately fail.

As the potential volume of the bag is as full of roots of the tree as compacted media allows, and even though there is apparently still some geotextile bag wall space left available for the roots to grow through, the tree may still die due to an inability to produce sufficient new roots. There appears to be a point where there will be a top which is too large to be sustained by an almost static growing root system. While the functional equilibrium theory suggests a reduction of leaf growth to compensate, the lack of opportunity of the root system to exploit any unimpeded space suggests the trees will die. The smallest bags provided strong indications of very little space within the bags left for further growth, and while alive, indications of trees in the smallest bag sizes suggest some may have died if allowed to grow for a fourth season. There was no indication from this experiment as to how long trees in larger bags would live, clearly the larger the bag, the greater the life expectancy as issues such as bulk density take much longer to have an effect.

A further difference between the restricted growth of a bonsai specimen and a tree grown in a geotextile fabric bag is that in the bonsai system the roots are trimmed and soil is removed annually from the outside of the root system making space for new root growth annually at the periphery of the roots, in space created just inside the container walls. In the geotextile fabric bag system the emphasis is made on the ability of the bag to restrict the root system within the fabric, therefore the loss of roots in this system is **outside** of the container and total containment of roots is made **inside the walls** of the geotextile fabric bag. The end results being;

- a) A deformed root system that includes large carbohydrate charged, restricted or reoriented roots, as well as smaller roots of a fibrous nature.
- b) Roots that as well as radiating outwards from the bag may travel in any direction depending upon space available and the least line of resistance. Roots may, as observed, reorientate

new growth to occupy space within the bag volume available, thus allowing virtually unrestricted growth to occur within the bag for a period of time. The likely impact being that the root system has a more 'normal' root tip to root length ratio in the early growth phase at least.

- c) Root pressure builds up from within the bag as secondary thickening develops from both roots and trunk. The geotextile fabric bag also comes under increasing tension from the volume expanding from the inside. From tests carried out placing fabric under lateral tension reduces the size and number of pre punched holes available for roots to grow through making it more difficult for roots to penetrate. Compacted media in the bag leads to an increase in bulk density, this in turn reduces the ability of new roots to explore the medium within the bag as time goes on. Expansion of root volume at the latter stages comes principally through secondary thickening. Finally roots that travel within the fabric walls, in the direction of the circumference, will eventually produce a significant root escape out of the bag.
- d) Unlike bonsai, roots cannot "assess" the limitations of the impermeable container wall. Roots are free in the permeable walled geotextile bags in the first instance to exit the fabric and exploit a volume of soil surrounding the bag, much larger than the volume of the bag itself.
- e) The surface area of bag wall available may itself provide insufficient opportunity in the long term for regeneration of roots to occur based on the ultimate size of the aerial tree that has grown and the progressive limitations of the root system to service it. Over time the root system becomes restricted by its own inventiveness and due to an inability to sense containment in its formative period of growth in bags. In the early phases of growth the tree has grown largely as though it were an unrestricted tree. Because of this the root system also grows rapidly becoming largely contained within the space in the bag and the tree is now likely to show increasing stress and regulation of the growth of the total tree. In this way the difference between bonsai and root restriction by geotextile fabric bags is most obvious.

- f) The tree grown in the geotextile fabric bag alters the balance between roots and shoots over time, from this study as the tree roots become more progressively contained, the root: shoot ratio reduces. In other unconfined trees, Harris (1992a) and others suggest that trees under stress would have a higher root : shoot ratio, this ratio changing as conditions for growth became more favourable.
- g) Root escapes alter the equation. Root escapes that occurred in the 'Tasman' poplars were observed toward the middle of the third growing season from cuttings. Root escapes allow the root unlimited exploration potential as there is no containment or restriction now to impede growth. Roots freed of such constraints produced trees with larger aerial growth than would be expected with comparable sized confined root systems. It was observed with some of the poplars that just one very large root emerged from one side of the bag. This root was the only root that was able to grow 'normally' and the process of tree growth that moves carbohydrate from the leaves to the roots supports the most active root observed in this trial. This main root grows rapidly and favours renewed growth of the aerial parts of the tree as well. The end result is the larger topped tree is blown over as the malformed root system pivots at right angles to the direction of that root during an incidence of high wind.

6.4. Fruiting versus non fruiting

A few *Dodonaea viscosa* 'Purpurea' produced a small quantity of flowers and fruit, this was not measured as it was assumed the quantity would not have affected other measurements. Other work on fruiting plants has shown root restriction reduces plant size and total yield, but relative to stem size frequently produces higher yields per trunk cross sectional area than non confined plants (Myers 1992, White 1995). Mature fruiting trees provide a sink for carbohydrate, this may assist the dwarfing process, based on the physiological state of the plant compared with a plant that may not be flowering or fruiting. The fruiting state of trees like apples that are able to shed carbohydrate annually may have the effect of reducing root growth for trees in geotextile fabric bags. The physiological stage of growth of trees fruiting is also different to that of trees in there early pre flowering growth phase. The tree in the fruiting phase combined with slower initial growth based on media type may grow in a different way to the trees used in this study. The key

concerns of root development in such a random manner within the bag and root escapes would both need to be investigated. Where additional sinks for carbohydrate are not going to be large, the nature of geotextile fabric bags for long term size control must be highly questionable. One of the common concerns that trees create for people is the mess made by fruitful ornamental trees. For street trees, high yields of fruit that may be caused by a tree shedding excess carbohydrate if grown in bags is likely to be a disadvantage. Examples of 'messy trees' often quoted include the Irish strawberry tree (*Arbutus unedo*), along with other such as sycamore (*Acer pseudoplatanus*).

Table 6.1.

Summary of differences

Bonsai system	Geotextile fabric bags
Container depth to diameter shallow	Container depth to diameter greater.
Container walls impermeable to root growth, therefore the space available is simply the volume within the container itself.	Container walls are permeable to root penetration, the roots are free to exit the bag exploiting a volume considerably larger than the bag volume up until the period when constriction occurs. Linear in bag restriction was not significant in <i>Populus</i> until end of 3rd growing season and in <i>Dodonaea</i> harvested after 2nd season .
Process of bonsai cuts roots and removes media from just inside container annually allowing space at periphery of roots to grow each year.	Roots occupy space in bags until max. volume is filled. Media in bags becomes highly compacted. Geotextile fabric is placed under increasing tension internally, needle punched holes become occluded, reduce in number and diameter.
Roots removed equate to biomass lost which is replaced from within the plant, helping control total tree growth.	No roots are removed from the system during growth in the manner of the bonsai system.
Roots removed from container, allowing regeneration and high root tips to root length ratio to occur.	Roots kept inside container, regeneration eventually slowed. Ratio of root tips to root length variable.
Roots form normally radiating outward from the trunk.	Roots radiate outward from the trunk initially, but when restricted may orientate in any direction within the bag.
Restriction occurs inside container.	Restriction occurs outside container.
Roots are relatively similar in size and are evenly balanced around the base of the trunk.	Root escapes may lead to the formation of just one large root escape as observed in the <i>Populus</i> .
Root tip to root length ratio may be kept relatively constant over much of the life of the tree.	Root length to root tip ratio, may change in favour of high root tip number to root length only after the bag volume has been largely exploited in terms of available space.
Growth is slow and appears to be more uniformly incremental. Continual creation of a small space at the periphery of the roots allows for longevity.	Initial growth may be rapid and slows only as the system is restricted within the bag, the inability to clear space for new growth will leads to root escapes or senescence and death .
The aerial parts of the tree remain in a physiological balance with the root system through the life of the tree.	Ultimately the architecture of the aerial parts of the tree will be out of balance with the root systems ability to service it, leaves and shoots will have to be closed down to match the now seriously compromised ability of the root system.

CHAPTER 7

AGRONOMIC IMPLICATIONS

7.1. Agronomic implications

Based on the results of this study the long term growth of trees in geotextile fabric bags in streets, using existing bag technology is not recommended. Poor root systems have resulted from growing trees in bags, the bag fabric has been shown to alter its characteristics with applied lateral tension. Trees are able to exit the bag by reorientating the direction of new roots within the circumference of the fabric. Roots that do exit in this manner rapidly grow unimpeded into the surrounding soil and this growth allows a corresponding increase in shoot growth. The final result for *Populus x canadensis*, particularly in the small bags, was the tree pivoting on one large root and when sufficient wind caught the top, the tree blew over. Trees in larger bags tended to produce a greater number of root escapes and tended to be more stable as a result. However, the root systems exhibited poor structure due to restriction imposed as a result of growing within the bags. Using geotextile fabric bags for street tree planting would not produce a satisfactory outcome as street trees are planted in any landscape situation for the long term.

7.2. Further research

For the geotextile bag system to work like bonsai the key issue is how you both restrict the roots within a geotextile fabric bag and more importantly, how do you at the same time create space at the periphery of the root system in order that roots can be limited in space, but annually grow outward. The bag system does not work in this way, instead a tree at planting has the maximum opportunity at that stage to exploit the medium both within the bag and outside it. The speed at which the tree can grow at this stage is determined largely by the nature of the media within the bag, temperature as dictated by season and by available water. Assuming good conditions for growth, the tree will grow rapidly at this stage as there is no effective barrier to growth. It is the nature of the growth of the tree itself that leads to restriction occurring. The faster the initial growth, the quicker restriction occurs. As the tree grows carbohydrate is apportioned to storage areas of the

tree including branches, trunk and roots, secondary thickening also develops. The pressure of the expanding diameter of the roots leads to compaction of the media within the bag, this in turn places the geotextile fabric bag under tension. The tension the fabric is placed under alters the nature of the fabric reducing the number and diameter of the needle punched holes available for roots to penetrate. As this pressure builds, compaction of media within the bag begins to limit moisture availability and aeration and these in turn limit growth of the tree. While speculative, ultimately the tree is likely to senesce and die. Assuming the fastest growth scenario initially, then the tree would probably die sooner than if it were to grow slowly from the start.

7.3. Ways of improving the current situation with bags

7.3.1. Assuming no changes to the fabric bags.

It is clear that the type of media influences the initial growth rate. In the longer term what is required is too slow growth initially, rather than allow fast tree growth to occur at the start. Slower restriction would allow more time before root growth occupies bag space in turn allowing extra time for flowering to commence. Earlier flowering would allow fruit produced to utilise carbohydrate produced sooner, reducing the amount going into root growth. As stated earlier, fruit produced will **not** enhance the value of this technique even assuming it might work for street trees, on the other hand for commercial fruiting plants this is worth considering. In this study, Templeton silt loam provided slower growth than the better aerated and well fertilised potting mix. Other soil mixes with a variety of particle sizes could be assessed, finer particle sizes indicating slower growth, but potentially allowing the tree a longer growing time within the confines of a bag. This may also allow turnover of roots to occur

7.3.2.. Changing the bag fabric

The problem with the existing fabric is that of the third dimension. It is the depth of the fabric that provided a means by which roots were able to escape. Roots were restricted whenever they penetrated the fabric walls at right angles, however, when they were able to grow tangentially and enter the fabric in the direction of the circumference, the root was then able to develop pressure

along the root length and build up sufficient radial strength to burst out of the bag. Assuming a third dimension is necessary in the fabric, then within the fabric wall, barriers that could effectively restrict root growth in the direction of the circumference needs to be engineered into the fabric.

The design of the current bag in time limits continual root growth of the tree, but not in the manner of bonsai as implied. Without the ability for roots to continually grow trees must eventually senesce and die. In order for the bag to properly work the bag must both restrict the growth of the tree, yet at the same time, allow some root growth to occur. The bag needs to be designed to allow some root growth annually. The current bag design fails in this respect as the bulk density of the media within the bag increases as root growth increases. Lifting and rebagging trees into larger bags every few years could be one option, although unlikely to be adopted. Another more preferable option might be a combination of growth regulators that are activated from within the bag, this could be engineered into the fabric to occur only when root pressure becomes such that antigibberellins for instance might slow growth sufficiently to prolong the life of a tree. The type of PGR could be some of the more modern antigibberellins that have a low water solubility and have been shown to be effective for a number of years. Alternatively, a PGR or herbicide that killed the root locally and allowed root senescence and consequently root turnover to occur would also be worth pursuing. Based on Gilman's (1996) experience with Biobarrier®, using a barrier alone simply encouraged roots to grow deeper and resurface beyond the barrier. For that reason the bag, providing containment, would probably need to be retained in some form.

7.4. Trees that sucker

Populus x canadensis 'Tasman' will produce root suckers under certain conditions. The use of a tree like poplar that has the ability to sucker even from small roots that would not be described as escapes suggests that they should not be grown in geotextile fabric bags.

7.5. Conclusion

The original hypothesis was that geotextile fabric bags would be suitable for long term restriction of street trees. This study showed that they are not. There are a great number of factors within the tree which interact and are effectively beyond a study such as this, however, the nature of

containment by the bag, the increasing root volume within the bag and the increasing bulk densities of the media provided sufficient evidence to override any other parameters that might have also some more subtle role to play leading to the results obtained.

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Appendix 1.

Treatments in Experiment One

- Tr 1 bag diameter 150mm, 4 l. bag volume, field soil, *Populus* 'Tasman'
- Tr 2 bag diameter 150mm, 4 l. bag volume, field soil, *Dodonaea viscosa* 'Purpurea'
- Tr 3 bag diameter 150mm, 4 l. bag volume, potting mix, *Populus* 'Tasman'
- Tr 4 bag diameter 150mm, 4 l. bag volume, potting mix, *Dodonaea viscosa* 'Purpurea'
- Tr 5 bag diameter 300mm, 224 l. bag volume, field soil, *Populus* 'Tasman'
- Tr 6 bag diameter 300mm, 24 l. bag volume, field soil, *Dodonaea viscosa* 'Purpurea'
- Tr 7 bag diameter 300 mm, 24 l. bag volume, potting mix, *Populus* 'Tasman'
- Tr 8 bag diameter 300mm, 24 l. bag volume, potting mix, *Dodonaea viscosa* 'Purpurea'
- Tr 9 bag diameter 450mm, 65 l. bag volume, field soil, *Populus* 'Tasman'
- Tr 10 bag diameter 450mm, 65 l. bag volume, field soil, *Dodonaea viscosa* 'Purpurea'
- Tr 11 bag diameter 450mm, 65 l. bag volume, potting mix, *Populus* 'Tasman'
- Tr 12 bag diameter 450mm, 65 l. bag volume, potting mix, *Dodonaea viscosa* 'Purpurea'
- Tr 13 bag diameter 600mm, 139 l. bag volume, field soil, *Populus* 'Tasman'
- Tr 14 bag diameter 600mm, 139 l. bag volume, field soil, *Dodonaea viscosa* 'Purpurea'
- Tr 15 bag diameter 600mm, 139 l. bag volume, potting mix, *Populus* 'Tasman'
- Tr 16 bag diameter 600 mm, 139 l. bag volume, potting mix, *Dodonaea viscosa* 'Purpurea'
- Tr 17 139 l. no bag, field soil, *Populus* 'Tasman'
- Tr 18 139 l. no bag, field soil soil, *Dodonaea viscosa* 'Purpurea'
- Tr 19 139 l. no bag, potting mix, *Populus* 'Tasman'
- Tr 20 139 l.no bag, potting mix, *Dodonaea viscosa* 'Purpurea'

Appendix 2. Field position & initial measurements of treatments *Dodonaea* - Sept.93

(top figure in each square = treatment no.- randomly allocated for the 2 species in 5 blocks of two rows), 2nd =height in cm, 3rd = base diameter of trunk in mm and final figure represents the colour grade 1=green, 2=green-purple, 3=purple-green, 4=purple. Single figures =*Populus* 'Tasman')

<- N.

6 69 5.3 1	3	7	5	4 65 5.3 3	11	13	9	1	20 71 6.6 3
2 68 5.3 1	8 66 5.3 3	15	17	14 84 6.4 3	16 76 5.8 2	10 65 4.8 2	12 72 4.7 2	18 73 6.4 2	19
4 79 5.8 4	3	9	2 73 6.8 1	12 71 5.8 3	1	18 66 4.8 2	5	6 67 4.9 2	17
8 67 6.5 1	15	16 70 5.4 2	11	13	19	20 68 4.9 2	7	14 80 6.8 1	10 66 55.6 2
17	4 85 6.4 3	14 76 6.7 2	1	19	16 64 4.8 2	8 73 5.9 2	3	9	20 74 5.6 4
7	5	15	2 74 5 4	6 76 6.1 1	11	18 62 5.9 1	10 57 4.8 2	12 73 6.3 1	13
4 68 5.2 2	17	20 78 5.7 1	11	2 63 5.6 2	3	15	5	7	1
14 68 5.9 1	10 63 5.1 2	16 65 5 2	18 80 4.9 2	9	6 78 5.3 1	13	12 65 4.8 2	19	8 71 6.3 1
12 76 5 2	8 60 5.5 1	4 66 5.9 3	9	18 61 4.8 2	19	5	15	3	10 65 5.2 2
16 60 4.1 2	6 70 4.9 3	11	20 76 5.9 2	17	2 68 5.9 1	14 67 5.9 2	1	13	7

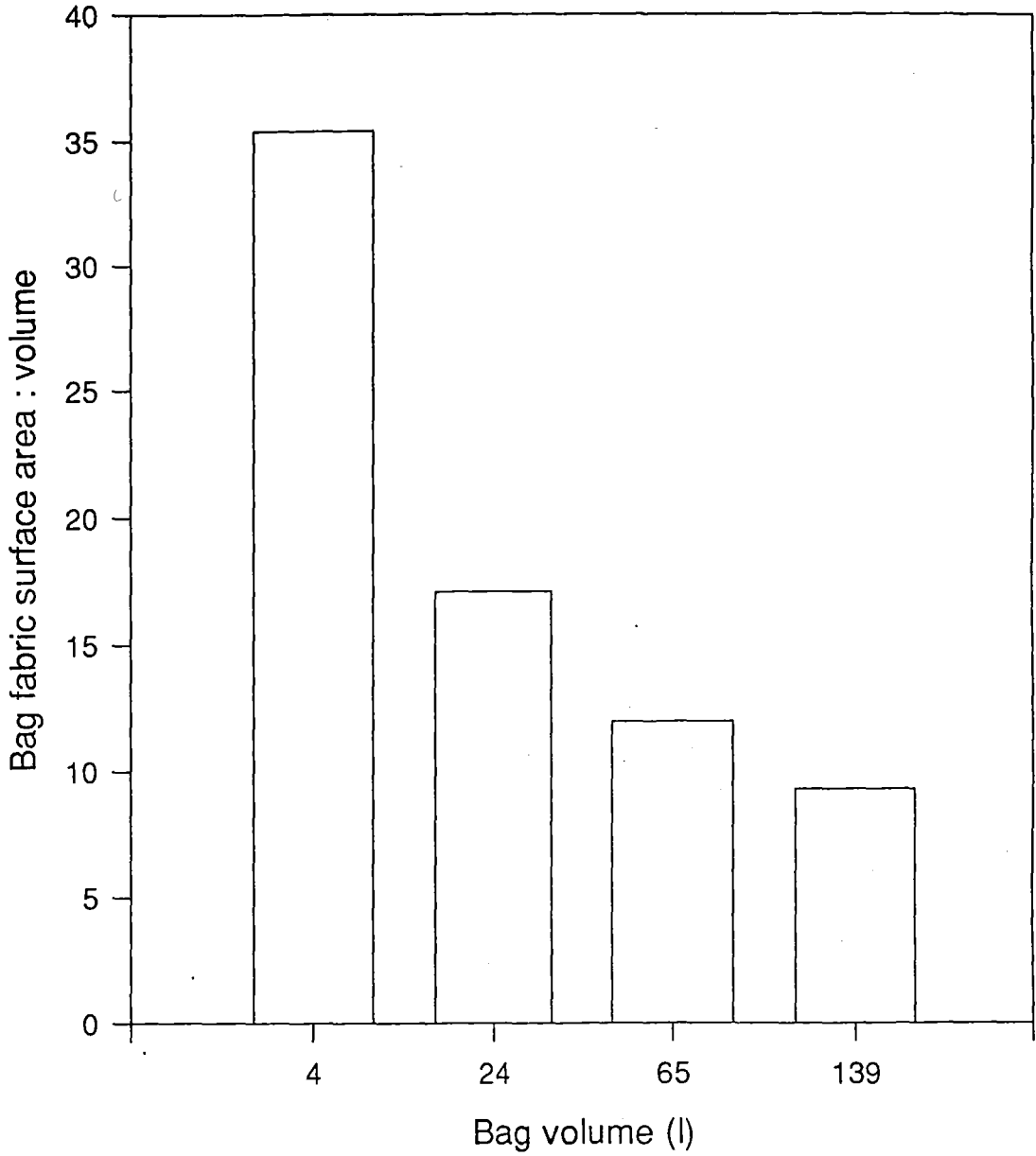
Appendix 3. Field placement and initial diameter measurements of poplar

<- N.

top number = treatment,
lower figure = diameter measurement 20mm from cutting top.
(note: Single figure in square = *Dodonaea* treatment numbers)

6	3 13.3	7 15.3	5 11.6	4	11 12	13 12.6	9 12.4	1 12.3	20
2	8	15 11.9	17 12.8	14	16	10	12	18	19 12.1
4	3 12.9	9 13.6	2	12	1 11.3	18	5 16.1	6	17 12.1
8	15 15.4	16	11 12.9	13 14.1	19 11	20	7 12.2	14	10
17 14.2	4	14	1 12.8	19 12.7	16	8	3 13.6	9 13.2	20
7 12.9	5 12.2	15 16.5	2	6	11 13.8	18	10	12	13 13.4
4	17 13.4	20	11 12.6	2	3 12.1	15 14.7	5 13.9	7 16	1 12.2
14	10	16	18	9 12.8	6	13 11.5	12	19 13.7	8
12	8	4	9 12.7	18	19 14.6	5 14.8	15 11.9	3 15.1	10
16	6	11 12.7	20	17 13	2	14	1 12.3	13 14.3	7 14.2

Appendix 4 Bag fabric surface area : volume



Appendix 5

Plate 1. *Populus* 'Tasman' roots having emerged directly from the trunk, reached the bag wall and have grown downward or along the inside of the bag wall in the direction of the circumference. (Roots in 24 litre bag, medium - soil).



Plate 2. Development of secondary lateral roots growing in line with the bag wall



Plates 3. and 4. **Root escapes from a 24 litre bag (above) and 139 litre bag (below).**
Both trees were growing in potting mix. Note the oblique angle
roots exited the bag.



Plate 5. Root growing along the bag wall and back in toward the trunk.



Plate 6. Winch lever, scales and tractor as anchor to measure force required to topple *Dodonaea viscosa* ‘Purpurea’ after 26 months growth



Plate 7. *Populus* ‘Tasman’ in small bag blown over toward the end of the third seasons growth. Tree pivots on large root escape

